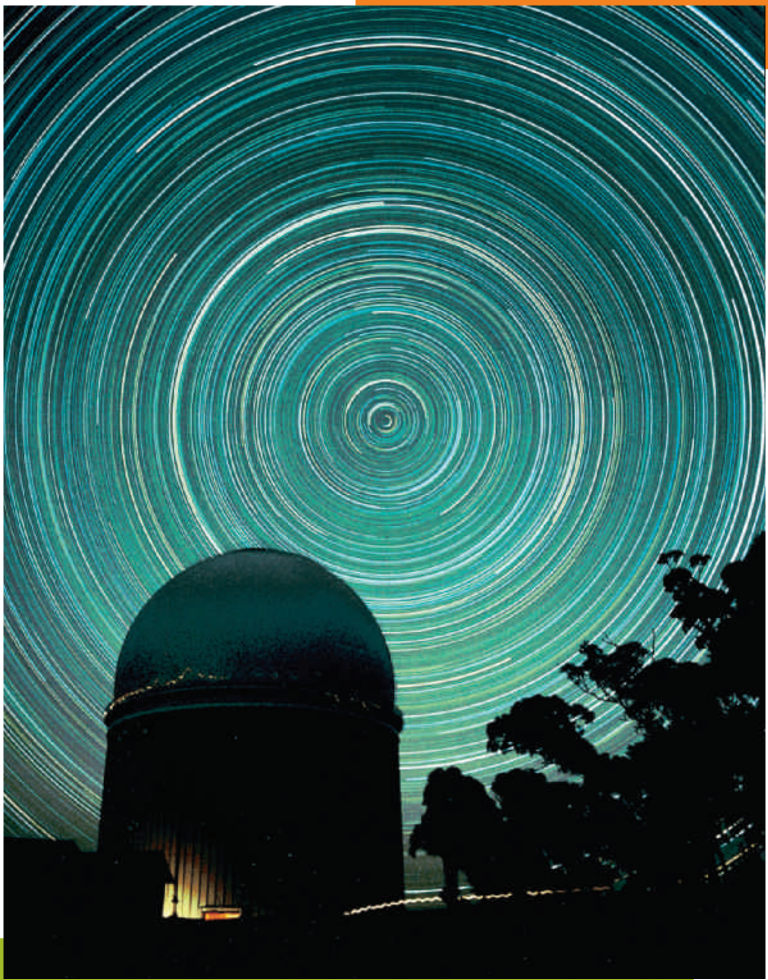
9

Classical Relativity

▶Everybody has been told that Earth rotates on its axis once each day, and yet it appears that the Sun, Moon, and stars all go around Earth. What evidence do we have to support the idea that it is Earth that is really moving?

(See page 181 for the answer to this question.)



David Malin/Anglo-Australian Observatory

The apparent motion of the stars is due to Earth's rotation.

DO observers moving relative to each other agree on the description of the motion of an object? Most of us feel that they would not. Consider, for example, the situation in which one observer is unfortunate enough to be in a free-falling elevator and the other is standing safely on the fifth floor. How do the two observers describe the motion of an apple that is "dropped" by the observer in the elevator?

The observer in the elevator sees the apple suspended in midair [Figure 9-1 (a)]. It has no speed and no acceleration. The observer on the fifth floor sees the apple falling freely under the influence of gravity. It has a constant downward acceleration and therefore is continually gaining speed [Figure 9-1 (b)].

Is there something fundamentally different about these descriptions, or are the differences just cosmetic? And most important, do the differences mean that the validity of Newton's laws of motion is in question? Are the laws valid for the observer in the elevator? If not, the consequences for our physics world view could be serious.

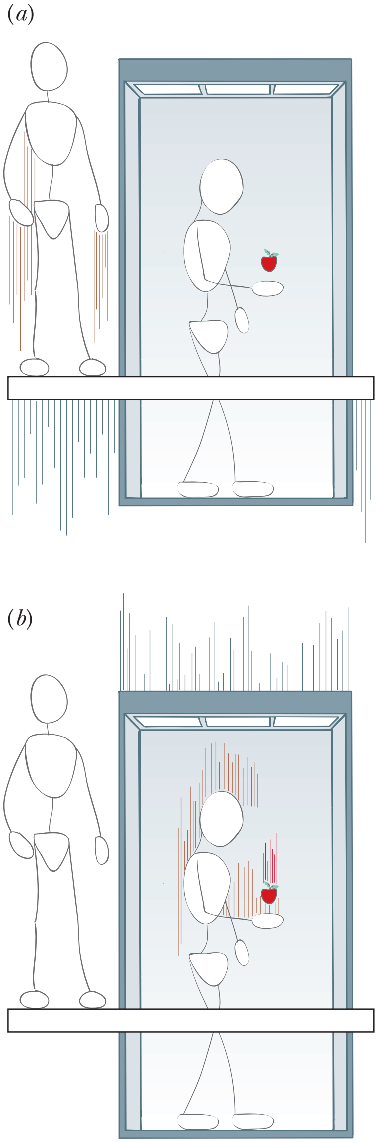


Figure 9-1 The dropped apple appears suspended in midair (a) as viewed by the elevator passenger and (b) as falling freely by the observer standing on the floor.

A Reference System

We see motion when something moves relative to other things. Imagine sitting in an airplane that is in straight, level flight at a constant speed. As far as the activities inside the plane are concerned, you don't think of your seat as moving. From your point of view, the seat remains in the same spot relative to everything else in the plane.

The phrase *point of view* is too general. Because all motion is viewed relative to other objects, we need to agree on a set of objects that are not moving relative to each other and that can therefore be used as the basis for detecting and describing motion. This collection of objects is called a **reference system**.

One common reference system is Earth. It consists of such things as houses, trees, and roads that we see every day. This reference system appears to be stationary. In fact, we are so convinced that it is stationary that we occasionally get tricked. If, while you sit in a car waiting for a traffic light to change, the car next to you moves forward, you occasionally experience a momentary sensation that your car is rolling backward. This illusion occurs because you expect your car to be moving and everything outside the car to be stationary.

It doesn't matter whether you are in a moving car or sitting in your kitchen; both are good reference systems. Consider your room as your reference system. To describe the motion of an object in the room, you measure its instantaneous position with respect to some objects in the room and record the corresponding time with a clock. This probably seems reasonable and quite obvious. But complications—and interesting effects—arise when the same motion is described from two different reference systems. We begin by studying these interesting effects in classical relativity.

Which car is moving?

Motions Viewed in Different Reference Systems

Imagine that you are standing next to a tree and some friends ride past you in a van, as shown in Figure 9-2. Suppose that the van is moving at a very high, constant velocity relative to you and that you have the ability to see inside the van.

One of your friends drops a ball. What does the ball's motion look like? When your friends describe the motion, they refer to the walls and floor of the van. They see the ball fall straight down and hit the van's floor directly below where it was released (Figure 9-3).

You describe the motion of the ball in terms of the ground and trees. Before the ball is released, you see it moving horizontally with the same velocity as your friends. Afterward, the ball has a constant horizontal component of velocity, but the vertical component increases uniformly. That is, you see the ball follow the projectile path shown in Figure 9-4.

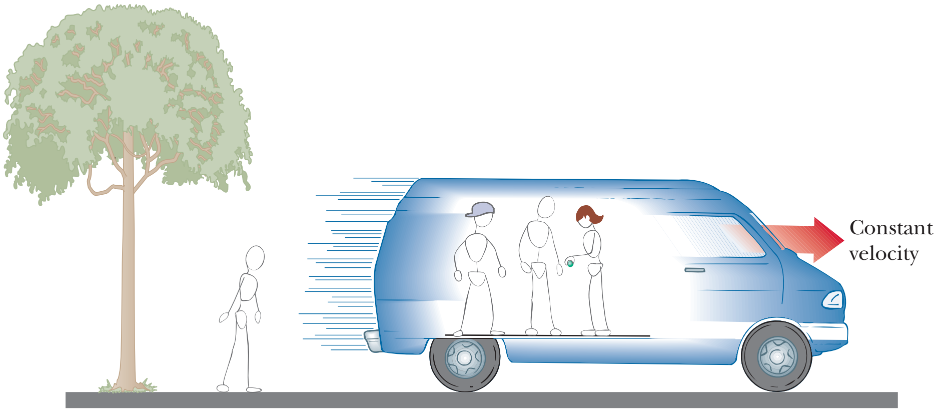


Figure 9-2 Your friends move past you at a high, constant velocity and drop a ball.

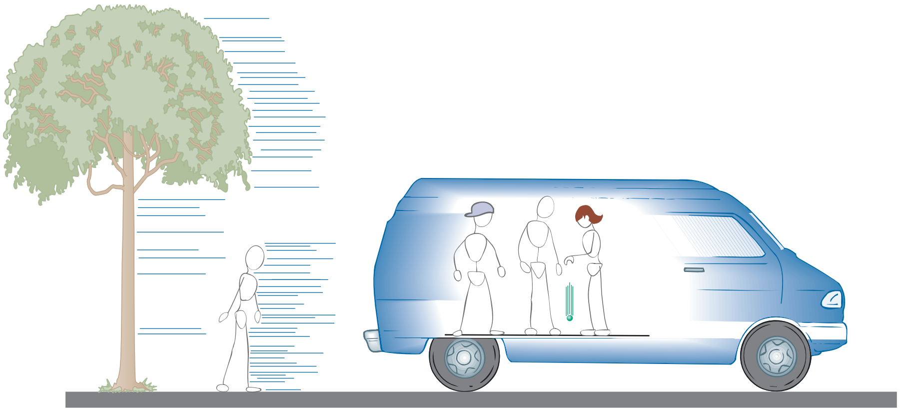


Figure 9-3 From your friends' point of view, they are at rest and see you moving. In their system they see the ball fall vertically.

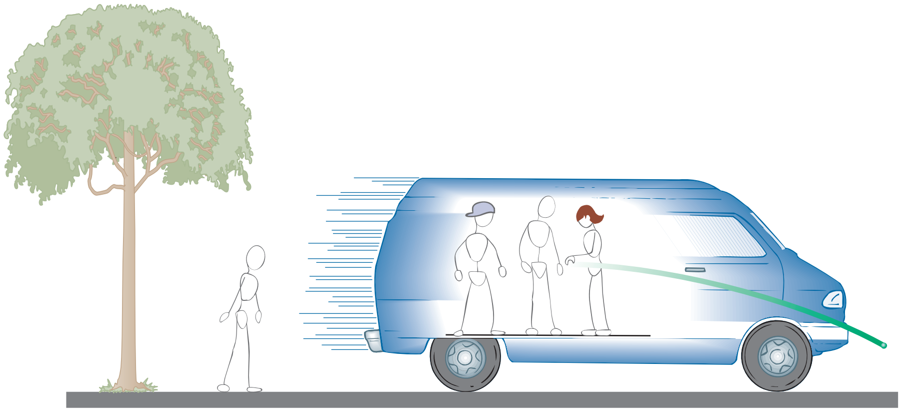


Figure 9-4 From the ground you see the ball follow a projectile path.

The ball's path looks quite different when viewed in different reference systems. Galileo asked whether observers could decide whose description was "correct." He concluded that they couldn't. In fact, each observer's description was correct. We can understand this by looking at the explanations that you and your friends give for the ball's motion.

We begin by examining the horizontal motion. Your friends, observing that the ball doesn't move horizontally, conclude that the net horizontal force is zero. On the other hand, you do see a horizontal velocity. But because it is constant, you also conclude that the net horizontal force is zero.

What about vertical forces? Your friends see the ball exhibit free fall with an acceleration of 10 (meters per second) per second. The vertical component of the projectile motion that you observe is also free-fall motion with the same acceleration. Each of you concludes that there is the same net constant force acting downward.

Although you disagree with your friends' description of the ball's path, you agree on the acceleration and the forces involved. Any experiments that you do in your reference system will yield the same accelerations and the same forces that your friends find in their system. In both cases, the laws of motion explain the observed motion.

We define an **inertial reference system** as one in which Newton's first law (the law of inertia) is valid. Each of the preceding systems was assumed to be an inertial reference system. In fact, any reference system that has a constant velocity relative to an inertial system is also an inertial system.

◀ **inertial reference system**

The principle that the laws of motion are the same for any two inertial reference systems is called the **Galilean principle of relativity**. Galileo stated that if one were in the hold of a ship moving at a constant velocity, there would be no experiment this person could perform that would detect the motion. This means that there is no way to determine which of the two inertial reference systems is "really" at rest. There seems to be no such thing in our universe as an absolute motion in space; all motion is relative.

The laws of physics are the same in all inertial reference systems.

◀ **principle of relativity**

The principle of relativity says that the laws of motion are the same for your friends in the van as they are for you. An important consequence is that the conservation laws for mass, energy, and momentum are valid in the van system as well as in the Earth system. If your friends say that momentum is conserved in a collision, you will agree that momentum is conserved even though you do not agree on the values for the velocities or momenta of each object.

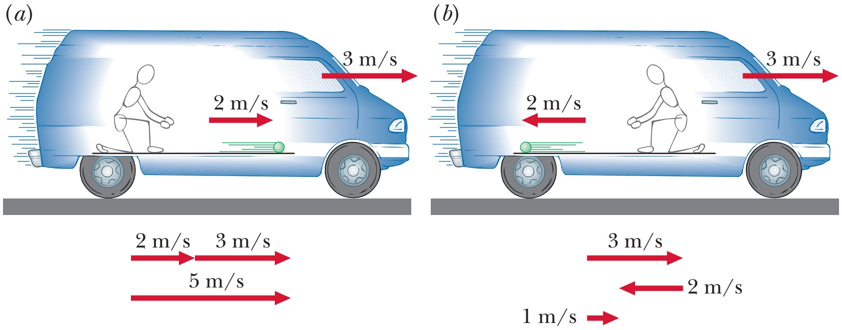
Comparing Velocities

◀ Extended presentation available in the *Problem Solving* supplement

Is there any way that you and your friends in the van can reconcile the different velocities that you have measured? Yes. Although you each see different velocities, you can at least agree that each person's observations make sense within their respective reference system. When you measure the velocity of the ball moving in the van, the value you get is equal to the *vector* sum of the van's velocity (measured in your system) and the ball's velocity (measured relative to the van).

Suppose your friends roll the ball on the floor at 2 meters per second due east and the van is moving with a velocity of 3 meters per second due east relative to your system. In this case the vectors point in the same direction, so you simply add the speeds to obtain 5 meters per second due east, as shown in Figure 9-5(a). If, instead, the ball rolls due west at 2 meters per second (relative to

Figure 9-5 The velocity of the ball relative to the ground is the vector sum of its velocity relative to the van and the van's velocity relative to the ground.



Q: What do you observe for the velocity of the ball if it is rolling eastward at 2 meters per second while the van is moving westward at 6 meters per second?

A: The ball is moving 4 meters per second westward.

the van's floor), you measure the ball's velocity to be 1 meter per second due east.

Although this rule works well for speeds up to millions of kilometers per hour, it fails for speeds near the speed of light, about 300,000 kilometers per second (186,000 miles per second). This is certainly not a speed that we encounter in our everyday activities. The fantastic, almost unbelievable, effects that occur at speeds approaching that of light are the subject of our next chapter.

Accelerating Reference Systems

Let's expand our discussion of your friends in the van. This time, suppose their system has a constant forward acceleration relative to your reference system. Your friends find that the ball doesn't land directly beneath where it was released but falls toward the back of the van, as shown in Figure 9-6. In your reference system, however, the path looks the same as before. It is still a projectile path with a horizontal velocity equal to the ball's velocity at the moment it was released. The ball stops accelerating horizontally when it is released, but your friends continue to accelerate. Thus, the ball falls behind.

As before, the descriptions of the ball's motion are different in the two reference systems. But what about the explanations? Your explanation of the motion—the forces involved, the constant horizontal velocity, and the constant vertical acceleration—doesn't change. But your friends' explanation does change; the law of inertia does not seem to work anymore. The ball moves off with a horizontal acceleration. In their reference system, they would have to apply a horizontal force to make an object fall vertically, a contradiction of the law of inertia. Such an accelerating system is called a **noninertial reference system**.

There are two ways for your friends to explain the motion. First, they can abandon Newton's laws of motion. This is a radical move requiring a different formulation of these laws for each type of noninertial situation. This is intuitively unacceptable in our search for universal rules of nature.

Second, they can keep Newton's laws by assuming that a horizontal force is acting on the ball. But this would indeed be strange; there would be a horizontal force in addition to the usual vertical gravitational force. This also poses problems. In inertial reference systems, we can explain all large-scale motion

FLAWED REASONING

Why is the following statement wrong? "If energy is conserved, it must have the same value in every inertial reference system."

ANSWER Kinetic energy is given by $\frac{1}{2}mv^2$. This formula depends on speed, so it must yield different values in different inertial systems. Take the example of a person on a moving train dropping a 1-kilogram ball from a height of 2 meters above the floor. In the system of the train, the ball initially has 20 joules of gravitational potential energy (relative to the floor) and no kinetic energy for a total of 20 joules. An observer on the ground, however, sees the ball initially moving with the same speed as the train, say, 30 meters per second. This observer agrees that the ball initially has 20 joules of gravitational potential energy but finds that the initial kinetic energy is 450 joules for a total of 470 joules. Conservation of energy simply means that just before the ball hits the floor, the person on the train will still calculate the total energy to be 20 joules, and the observer on the ground will still calculate the total energy to be 470 joules.

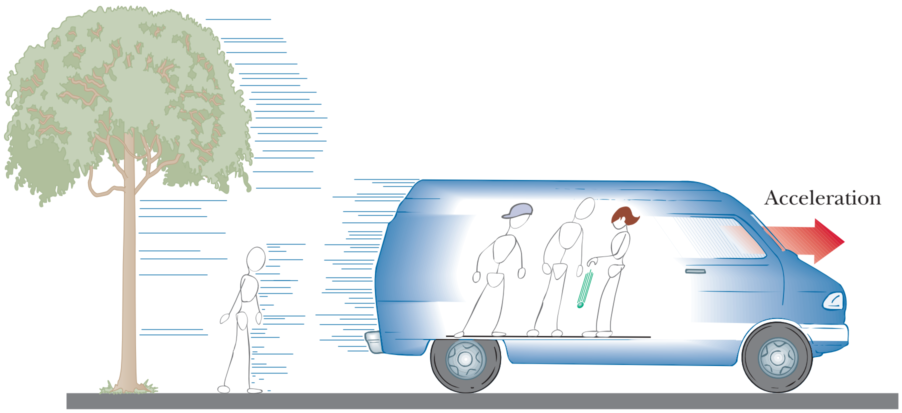


Figure 9-6 In an accelerating system, your friends see the ball fall toward the back of the van.

Q: Where would the ball land if the van were slowing down?

A: It would land forward of the release point because the ball continues moving with the horizontal velocity it had when released, whereas the van is slowing down.

in terms of gravitational, electric, or magnetic forces. The origin of this new force is unknown; furthermore, its size and direction depend on the acceleration of the system. We know, from your inertial reference system, that the strange new force your friends seem to experience is due entirely to their accelerated motion. Forces that arise in accelerating reference systems are called **inertial forces**.

If inertial forces seem like a way of getting around the fact that Newton's laws don't work in accelerated reference systems, you are right. These forces do not exist; they are invented to preserve the Newtonian world view in reference systems where it does not apply. In fact, another common label for these forces is *fictitious forces*.

If you are in the accelerating system, these fictitious forces seem real. We have all felt the effect of being in a noninertial system. If your car suddenly changes its velocity—speeding up, slowing down, or changing direction—you feel pushed in the direction opposite the acceleration. When the car speeds up rapidly, we often say that we are being pushed back into the seat.

Q: What is the direction and cause of the fictitious force you experience when you suddenly apply the brakes in your car?

A: Assuming that you are moving forward, the inertial force acts in the forward direction, "throwing" you toward the dashboard. It arises because of the car's acceleration in the backward direction due to the braking.

Realistic Inertial Forces

If you were in a windowless room that suddenly started accelerating relative to an inertial reference system, you would know that something had happened. You would feel a new force. Of course, in this windowless room, you wouldn't have any visual clues to tell you that you were accelerating; you would only know that some strange force was pushing in a certain direction.

This strange force would seem very real. If you had force measurers set up in the room, they would all agree with your sensations. This experience would be rather bizarre; things initially at rest would not stay at rest. Vases, chairs, and even people would need to be fastened down securely, or they would move.

This situation occurs whenever we are in a noninertial reference system. Imagine riding in an elevator accelerating upward from Earth's surface. You would experience an inertial force opposite the acceleration in addition to the gravitational force. In this case the inertial force would be in the same direction as gravity, and you would feel "heavier." You can even measure the change by standing on a bathroom scale.

If the elevator stands still or moves with a constant velocity, a bathroom scale indicates your true weight [Figure 9-7(a)]. Because your acceleration is zero, the net force on you must also be zero. This means that the normal force $\mathbf{N}_{scale,you}$ exerted on you by the scale must balance the gravitational force $\mathbf{W}_{Earth,you}$ exerted on you by Earth, and therefore $\mathbf{N}_{scale,you}$ is equal to and opposite of $\mathbf{W}_{Earth,you}$ (not by Newton's third law, but by Newton's second law with zero acceleration). Because the size of the gravitational force is equal to the mass m times the acceleration due to gravity g, we sometimes say that you experience a force of 1 "g."

If the elevator accelerates upward [Figure 9-7(b)], you must experience a net upward force as viewed from the ground. Because the gravitational force does not change, the normal force $\mathbf{N}_{scale,you}$ exerted on you by the scale must be larger than the gravitational force $\mathbf{W}_{Earth,you}$. This change in force would register as a heavier reading on the scale. You would also experience the effects on your body. Your stomach would "sink" and you would feel heavier. Your "apparent weight," the reading on the scale, has increased.

If the upward acceleration is equal to that of gravity, the net upward force on you must have a magnitude equal to $\mathbf{W}_{Earth,you}$. Therefore, the scale must exert a force equal to twice $\mathbf{W}_{Earth,you}$, and the reading shows this. You experience a force of 2 g's and feel twice as heavy. Astronauts experience maximum forces of 3 g's during launches of the space shuttle. During launches of the Apollo missions to the Moon, the astronauts experienced up to 6 g's. When pilots eject from jet fighters, the forces approach 20 g's for very short times.

Figure 9-7(c) shows the situation as seen from the ground when the elevator accelerates in the downward direction. In the elevator the inertial force

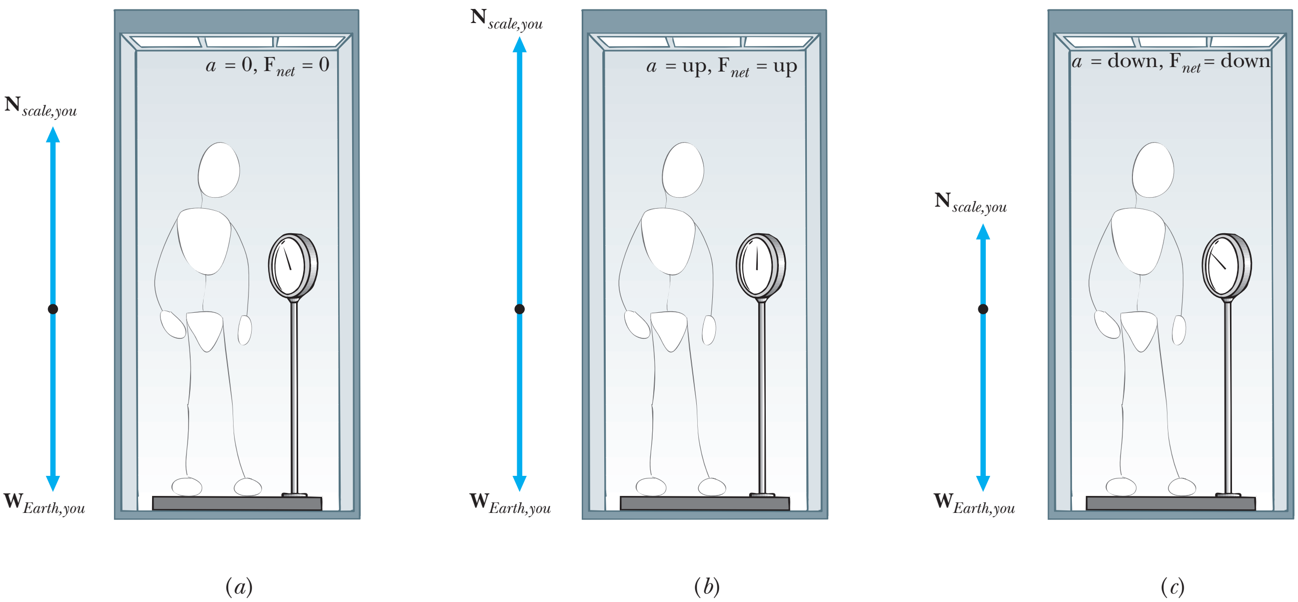


Figure 9-7 (a) The apparent weight $\mathbf{N}_{scale,you}$ is the reading on the scale, and is equal in magnitude to the true weight (the gravitational force) $\mathbf{W}_{Earth,you}$ when the elevator has no acceleration; (b) $\mathbf{N}_{scale,you}$ is larger than $\mathbf{W}_{Earth,you}$ when the elevator accelerates upward; and (c) $\mathbf{N}_{scale,you}$ is smaller than $\mathbf{W}_{Earth,you}$ when the elevator accelerates downward.

Q: If you are traveling upward in the elevator and slowing down to stop at a floor, will the scale read heavier or lighter?

A: Because you are slowing while traveling upward, the acceleration is downward and therefore the inertial force is upward and the scale will read lighter.

is upward and subtracts from the gravitational force. You feel lighter; your apparent weight is less than your true weight.

If the downward acceleration is equal to that of gravity, you feel *weightless*. Your true weight, the gravitational force $\mathbf{W}_{Earth,you}$, has not changed. You and the elevator are both accelerating downward at the acceleration due to gravity. The bathroom scale does not exert any force on you, and your apparent weight is zero. You appear to be "floating" in the elevator, a situation sometimes referred to as "zero g."

If somehow your elevator accelerates in a sideways direction, the extra force is like the one your friends felt in the van; the inertial force is horizontal and opposite the acceleration. During the takeoff of a commercial jet airplane, passengers typically experience horizontal accelerations of $\frac{1}{4}$g.

Fasten a cork to the inside of the lid of a quart jar with a string that is approximately three-fourths the height of the jar, as shown in Figure 9-8(a). Fill the jar with water, put the lid on tight, and invert the jar. The cork floats

NASA

This sequence of photographs taken during the experiments before the first spaceflight shows the effects of inertial forces during large accelerations.

Everyday Physics | *Living in Zero G*

Astronauts in space stations orbiting Earth experience weightlessness—"zero g." They float about the station and can do gymnastic maneuvers involving a dozen somersaults and twists. They can release objects and have them stay in place suspended in the air. This happens because the astronauts (and other "floating" objects) are in orbit about Earth just like the space station. Even when the astronauts leave the space station to go for a space "walk," the effect is the same: they float along with the space station.

Of course, when the astronauts try to move a massive object, they still experience the universality of Newton's second law; being weightless does not mean being massless.

Although they experience the sensation of being weightless, the gravitational force on them is definitely *not* zero; at an altitude of a few hundred kilometers, the gravitational force is approximately 10% lower than at Earth's surface. In the accelerating, noninertial reference system of the space station, the gravitational force and the inertial force cancel each other, producing the sensation of weightlessness. Any experiment they could perform inside the space station, however, yields the same result; gravity appears to have been turned off.

Although living in zero g is a pleasant experience for a while, it can create problems over long periods of time because our bodies have evolved in a gravitational field. Astronauts report puffiness in the face, presumably from body fluids not being held down by gravity. Scientists also report that changes occur in astronauts' hearts because of the lower stress levels—sort of the reverse of exercise. For longer periods of living in zero g, bone growth may be impaired.

All these issues will need to be addressed in the next decade as the United States and Russia develop plans to send astronauts and cosmonauts to Mars. Such a trip will require several years, much longer than the record 439 days for living in zero g held by the Russians.

1. An astronaut has mass of 60 kg. Find her true weight, $\mathbf{W}_{Earth,astronaut}$, on Earth and while orbiting Earth in the space station.
2. A sense of weightlessness may also be experienced in a plane called the "Vomit Comet." In what way is the motion of this plane similar to the motion of the space station?

NASA

Astronauts working in the Spacelab science module in *Atlantis*'s cargo bay.

NASA

Flight engineer Susan Helms and mission commander Yury Usachev aboard the U.S. Laboratory Destiny module of the International Space Station in April 2001.

up, opposite the direction of the gravitational force. Which way does the cork swing when the jar is accelerated in the forward direction, as in the van in Figure 9-6? We find that the cork swings forward [Figure 9-8(b)]. In this noninertial reference system we can still claim that the cork floats "up," but we must redefine what we mean by *up*. In the noninertial reference system, "up" is defined as the direction opposite the vector sum of the gravitational force and any inertial (fictitious) forces. If we could grow bean sprouts in a van that was always accelerating in the forward direction, they would grow "up" in the direction indicated by Figure 9-8(b).

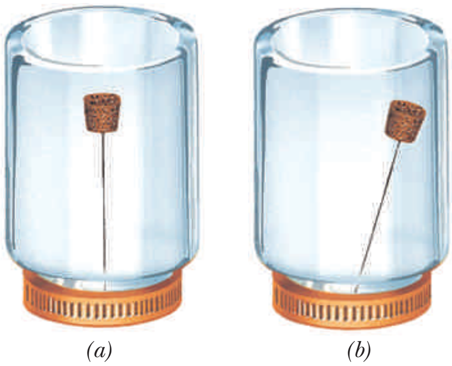


Figure 9-8 (a) The cork floats up in an inertial reference system, opposite the direction of the gravitational force. (b) In a noninertial (accelerating) reference system, "up" is defined as the direction opposite the vector sum of the gravitational force and any inertial forces.

Centrifugal Forces

A rotating reference system—such as a merry-go-round—is also noninertial. If you are on the merry-go-round, you feel a force directed outward. This fictitious force is the opposite of the centripetal force we discussed in Chapter 4 and is called the **centrifugal force**. It is present only when the system is rotating. As soon as the ride is over, the centrifugal force disappears.

Consider the Rotor carnival ride, which spins you in a huge cylinder [Figure 9-9(a)]. As the cylinder spins, you feel the fictitious centrifugal force pressing you against the wall. When the cylinder reaches a large enough rotational speed, the floor drops out from under you. You don't fall, however, because the centrifugal force pushing you against the wall increases the frictional force with the wall enough to prevent you from sliding down the wall. If you try to "raise" your arms away from the wall, you feel the force pulling them back to the wall.

Somebody looking into the cylinder from outside (an inertial system) sees the situation shown in Figure 9-9(b); the only force is the centripetal one acting inward. Your body is simply trying to go in a straight line, and the wall is exerting an inward-directed force on you, causing you to go in the circular path. This real force causes the increased frictional force.

An artificial gravity in a space station can be created by rotating the station. A person in the station would see objects "fall" to the floor and trees grow "up." If the space station had a radius of 1 kilometer, a rotation of about once every minute would produce an acceleration of 1 g near the rim. Again, viewed from a nearby inertial system, the objects don't fall, they merely try to go in straight lines. Living in this space station would have interesting consequences. For example, climbing to the axis of rotation would result in "gravity" being turned off.

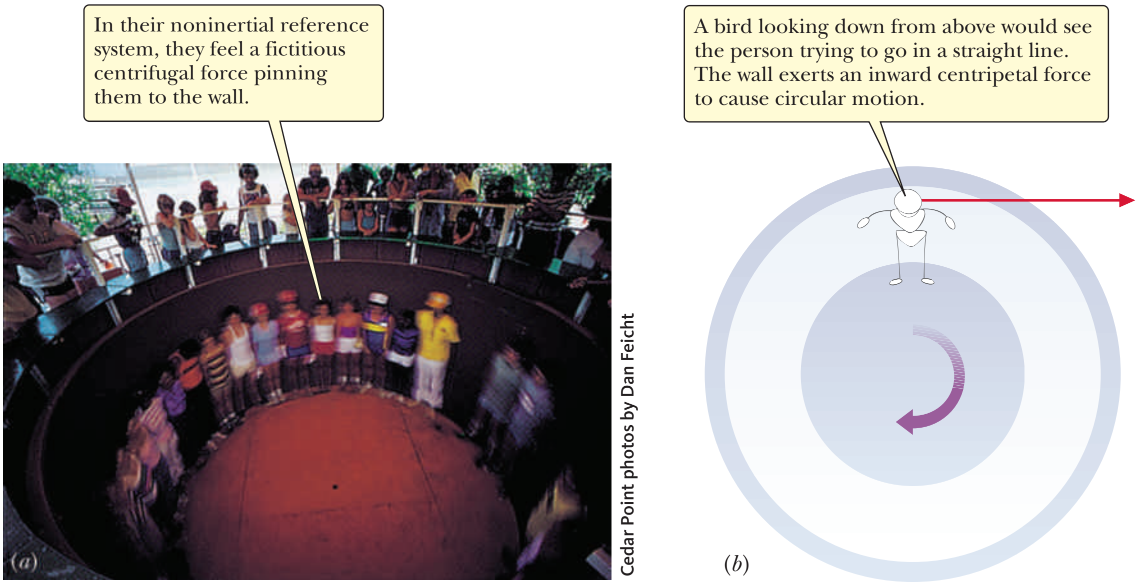


Figure 9-9 Although the people in the Rotor feel forces pushing them against the wall, an inertial observer says that the wall must push on the people to make them go in a circle.

FLAWED REASONING

You are riding in the Rotor at the state fair, as shown in Figure 9-9. A friend explains that two equal and opposite forces are acting on you, a centripetal force inward and a centrifugal force outward. Your friend further explains that these forces are third-law forces. **Are there some things that you should not learn from your friend?**

ANSWER Third-law forces never act on the same object, so these two "forces" cannot form a third-law pair. In the inertial system, there is only one force acting on you: the centripetal force exerted by the wall on your back. This force causes you to accelerate in a circle. The third-law companion to this force is the push your back exerts on the wall. In your noninertial frame you are at rest, so you invent a fictitious force acting outward to balance the push by the wall. This outward "force" is not a real force.

Q: What is the net force on someone standing on the floor of the rotating space station as viewed from his or her reference system?

A: The net force would be zero because the person is at rest relative to the floor. The pilot of an approaching spaceship would see a net centripetal force acting on the person in the space station.

Earth: A Nearly Inertial System

Earth is moving. This is probably part of your commonsense world view because you have heard it so often. But what evidence do you have to support this statement? To be sure that you are really a member of the moving-Earth society, point in the direction that Earth is moving right now. This isn't easy to do.

We do not feel our massive Earth move, and it seems more likely that it is motionless. But in fact it is moving at a very high speed. A person on the equator travels at about 1700 kilometers per hour because of Earth's rotation. The speed due to Earth's orbit around the Sun is even larger: 107,000 kilometers per hour (67,000 miles per hour)!

What led us to accept the idea that Earth is moving? If we look at the Sun, Moon, and stars, we can agree that *something* is moving. The question is this: are the heavenly bodies moving and is Earth at rest, or are the heavenly bodies at rest and Earth is moving?

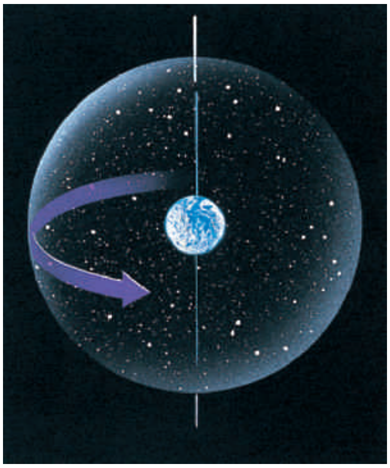


Figure 9-10 The geocentric view of the universe has Earth at its center.

The Greeks believed that the motion was due to the heavenly bodies traveling around a fixed Earth located in the center of the universe. This scheme is called the **geocentric model**. They assumed that the stars were fixed on the surface of a huge celestial sphere with Earth at its center (Figure 9-10). This sphere rotated on an axis through the North and South Poles, making one complete revolution every 24 hours. You can easily verify that this model describes the motion of the stars by observing them during a few clear nights.

The Sun, Moon, and planets were assumed to orbit Earth in circular paths at constant speeds. When this theory did not result in a model that could accurately predict the positions of these heavenly bodies, the Greek astronomers developed an elaborate scheme of bodies moving around circles that were in turn moving on other circles, and so on. Although this geocentric model was fairly complicated, it described most of the motions in the heavens.

This brief summary doesn't do justice to the ingenious astronomical picture developed by the Greeks. The detailed model of heavenly motion developed by Ptolemy in AD 150 resulted in a world view that was accepted for

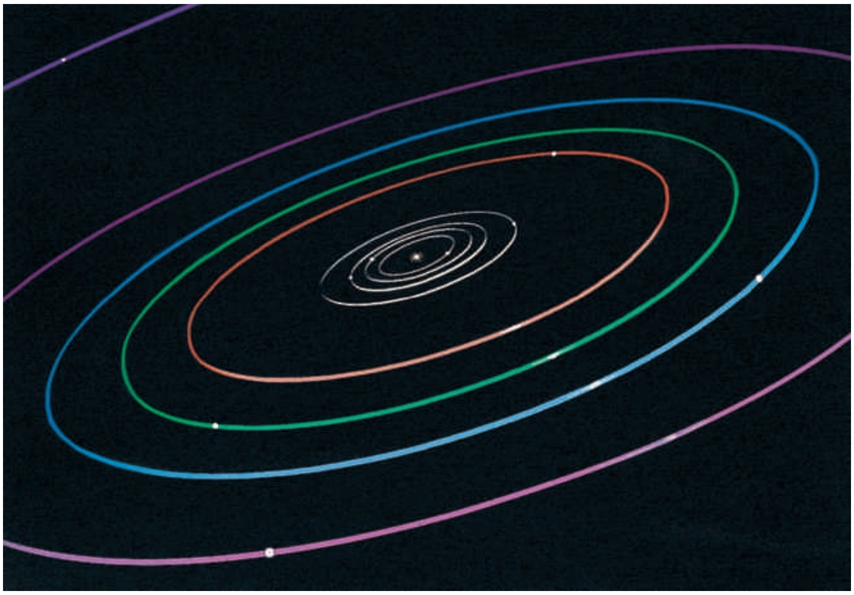


Figure 9-11 In the heliocentric model of the solar system, the planets orbit the Sun.

1500 years. Ptolemy's theory was so widely accepted because it predicted the positions of the Sun, Moon, planets, and stars accurately enough for most practical purposes. It was also very comforting for philosophic and religious reasons. It accorded well with Aristotle's view of Earth's central position in the universe and humankind's correspondingly central place in the divine scheme of things.

In the 16th century, a Polish scientist named Copernicus examined technical aspects of this Greek legacy and found them wanting. In 1543 his powerful and revolutionary astronomy offered an alternative view: Earth rotated about an axis once every 24 hours while revolving about the Sun once a year. Only the Moon remained as a satellite of Earth; the planets were assumed to orbit the Sun. Because his proposal put the Sun in the center of the universe, it is called the **heliocentric model** (Figure 9-11).

Q: Which way does Earth rotate, toward the east or west?

A: Earth rotates toward the east, making the stars appear to move to the west.

How does one choose between two competing views? One criterion—simplicity—doesn't help here. Although Copernicus's basic model was simpler to visualize than Ptolemy's, it required about the same mathematical complexity to achieve the same degree of accuracy in predicting the positions of the heavenly bodies.

A second criterion is whether one model can explain more than the other. Here Copernicus was the clear winner. His model predicted the order and relative distances of the planets, explained why Mercury and Venus were always observed near the Sun, and included some of the details of planetary motion in a more natural way. It would seem that the Copernican model should have quickly replaced the older Ptolemaic model.

But the Copernican model appeared to fail in one crucial prediction. Copernicus's model meant that Earth would orbit the Sun in a huge circle. Therefore, observers on Earth would view the stars from vastly different positions during Earth's annual journey around the Sun. These different positions would provide different perspectives of the stars, and thus they should

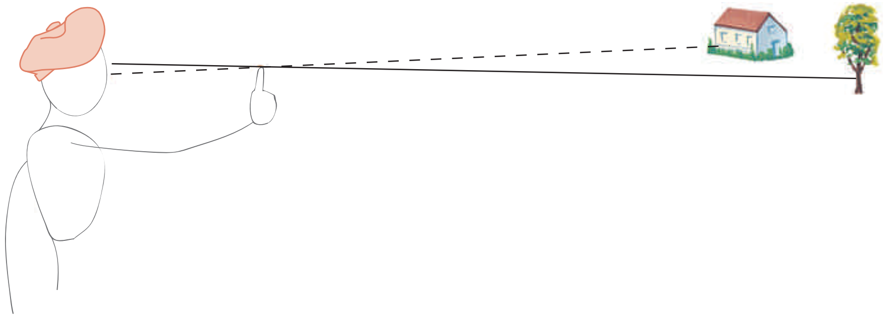


Figure 9-12 The position of the finger changes relative to the background when viewed by the other eye.

Copernicus's critics argued that if Earth were moving, birds would be left behind.

be observed to shift their positions relative to each other on an annual basis. This shift in position is called *parallax.*

You can demonstrate parallax to yourself with the simple experiment shown in Figure 9-12. Hold a finger in front of your face and look at a distant scene with your left eye only. Now look at the same scene with only your right eye. Because your eyes are not in the same spot, the two views are not the same. You see a shifting of your finger relative to the distant scene. Notice also that this effect is more noticeable when your finger is close to your face.

Unfortunately for Copernicus, the stars did not exhibit parallax. Undaunted by the lack of results, Copernicus countered that the stars were so far away that Earth's orbit about the Sun was but a point compared to the distances to the stars. Instruments were too crude to measure this effect. Although his counterclaim was a possible explanation, the lack of observable parallax was a strong argument against his model and delayed its acceptance. The biggest stellar parallax is so small that it was not observed until 1838—300 years later.

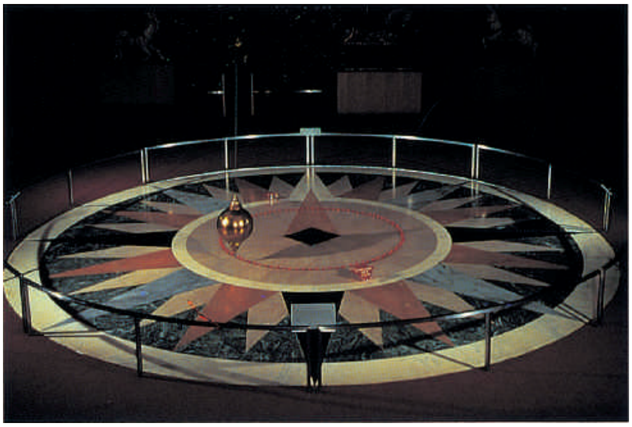
There was another problem with Copernicus's model. Copernicus developed these ideas before Galileo's time and did not have the benefit of Galileo's work on inertia or inertial reference systems. Because it was not known that all inertial reference systems are equivalent, most people ridiculed the idea that Earth could be moving: after all, one would argue, if a bird were to leave its perch to catch a worm on the ground, Earth would leave the bird far behind! For these reasons the ideas of Copernicus were not accepted for a long time. In fact, 90 years later Galileo was being censured for his heretical stance that Earth does indeed move.

One of the reasons that it took thousands of years to accept Earth's motion is that Earth is very nearly an inertial reference system. Were Earth's motion undergoing large accelerations, the effects would have been indisputable. Even though the inertial forces are very small, they do provide evidence of Earth's motion.

Noninertial Effects of Earth's Motion

A convincing demonstration of Earth's rotation was given by French physicist J. B. L. Foucault around the middle of the 19th century. He showed that the plane of swing of a pendulum appears to rotate. Foucault's demonstration is very popular in science museums; almost every one has a large pendulum with a sign saying that it shows Earth's rotation. But how does this show that Earth is rotating?

First, we must ask what would be observed in an inertial system. In the inertial system, the only forces on the swinging bob are the tension in the string and the pull of gravity; both of these act in the plane of swing. So in an inertial system, there is no reason for the plane to change its orientation.



John Kielkopf/Dept. of Physics & Astronomy/ University of Louisville

A Foucault pendulum shows that Earth rotates.

The noninertial explanation is simplest with a Foucault pendulum on the North Pole, as shown in Figure 9-13. The plane of the pendulum rotates once every 24 hours; that is, if you start it swinging along a line on the ground, some time later the pendulum will swing along a line at a slight angle to the original line. In 12 hours it will be along the original line again (the pendulum's plane is halfway through its rotation). Finally, after 24 hours the pendulum will once again be realigned with the original line. If you lie on your back under the pendulum and observe its motion with respect to the distant stars, you will see that the plane of the pendulum remains fixed relative to them. It is Earth that is rotating.

At more temperate latitudes, the plane of a Foucault pendulum requires longer times to complete one rotation. The time increases continuously from the pole to the equator, with the time becoming infinite at the equator; that is, the plane does not rotate.

The apparent weight of a person on Earth (the reading on a bathroom scale) is affected by Earth's rotation. A person on the equator is traveling along a circular path, but a person on the North Pole is not. The person on

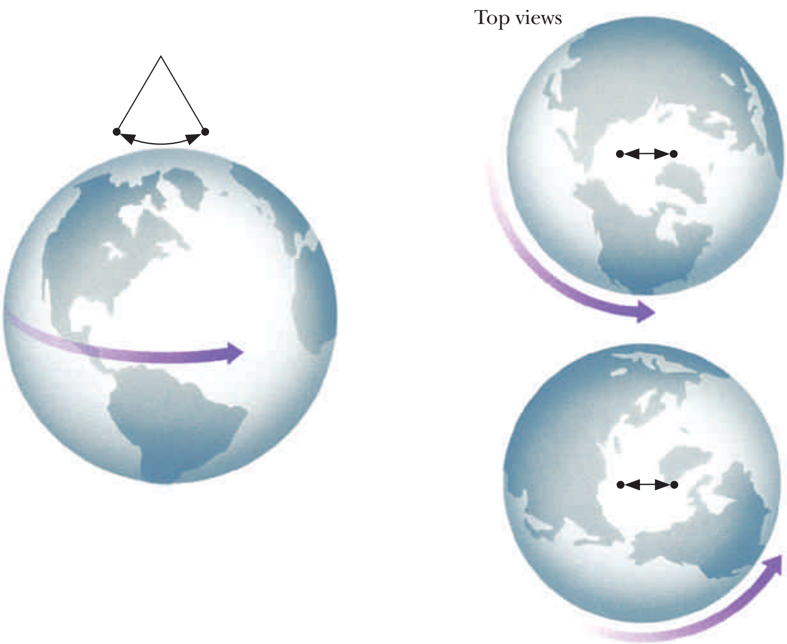
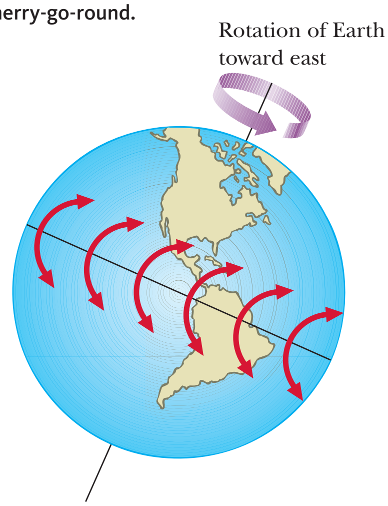


Figure 9-13 A Foucault pendulum at the North Pole appears to rotate relative to the ground once in 24 hours.

You can experience the effects of the Coriolis force by playing catch while riding on a merry-go-round.



Air moving poleward from the Equator is traveling east faster than the land beneath it and veers to the east (turns right in the Northern Hemisphere and left in the Southern Hemisphere).

Air moving toward the Equator is traveling east slower than the land beneath it and veers to the west (turns right in the Northern Hemisphere and left in the Southern Hemisphere).

Coriolis effect. Air moving north or south is deflected by Earth's rotation.

the North Pole feels the force of gravity; the person on the equator feels the force of gravity plus the fictitious centrifugal force. The effect of this centrifugal force is small; it is only one-third of 1% of the gravitational force. That means if we transported a 1-newton object from the North Pole to the equator, its apparent weight would be 0.997 newton.

Another inertial force in a rotating system, known as the **Coriolis force**, is the fictitious force you feel when you move along a radius of the rotating system. If, for example, you were to walk from the center of a merry-go-round to its edge, you would feel a force pushing you in the direction opposite the rotation.

From the ground system, the explanation is straightforward. A point on the outer edge of a rotating merry-go-round has a larger speed than a point closer to the center because it must travel a larger distance during each rotation. As you walk toward the outer edge, the floor of the merry-go-round moves faster and faster. Your inertial tendency is to keep the same velocity relative to the ground system. The merry-go-round moves out from under you, giving you the sensation of being pulled in the opposite direction. If you move inward toward the center of the merry-go-round, the direction of this inertial force is reversed. The Coriolis force is more complicated than the centrifugal force in that it depends on the velocity of the object in the noninertial system as well as the acceleration of the system.

The Coriolis force acts on anything moving along Earth's surface and deflects it toward the right in the Northern Hemisphere and toward the left in the Southern Hemisphere. British sailors experienced this reversal during World War I. During a naval battle near the Falkland Islands (50 degrees south latitude), they noticed that their shells were landing about 100 meters to the left of the German ships. The Coriolis corrections that were built into their sights were correct for the Northern Hemisphere but were in the wrong direction for the Southern Hemisphere!

The Coriolis force also causes large, flowing air masses in the Northern Hemisphere to be deflected to the right. As the air flows in from all directions toward a low-pressure region, it is deflected to the right, as illustrated in Figure 9-14. The result is that hurricanes in the Northern Hemisphere rotate

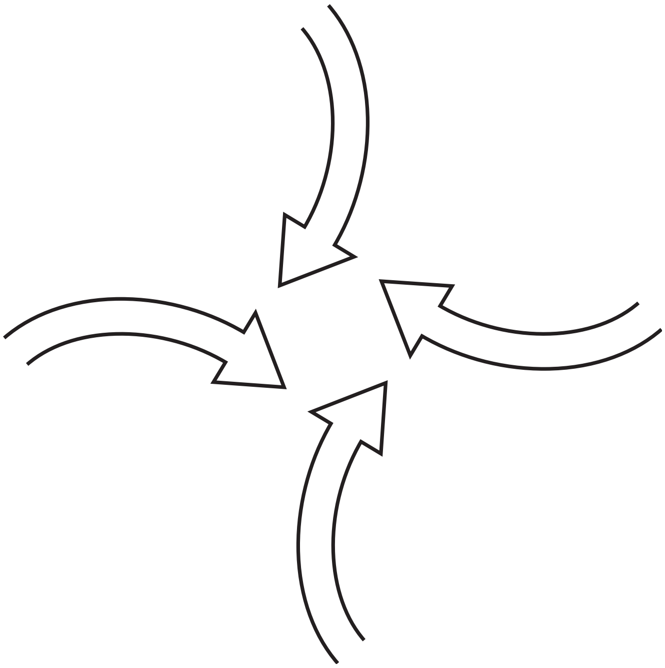
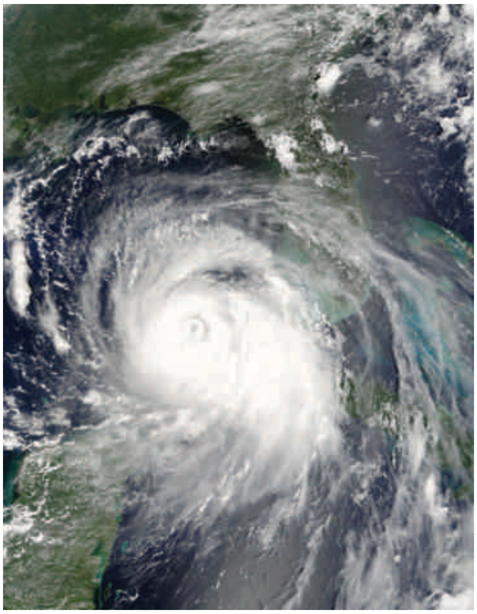


Figure 9-14 Air flows into the low pressure storm center from all directions. The Coriolis force causes this flow to curve to the right, causing a counter-clockwise circulation around the eye of the storm.

Are You On the Bus?

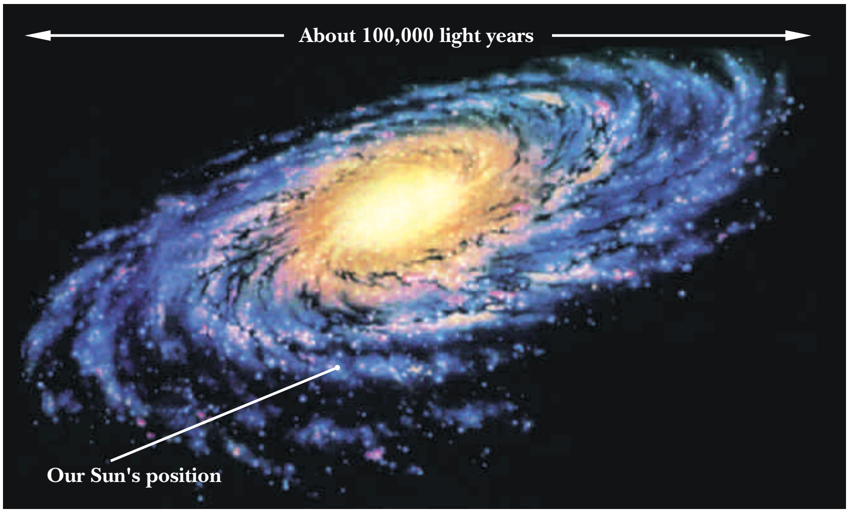
Q: If you drop a ball from a great height, it experiences a Coriolis force. Will the ball be deflected to the east or the west?

A: This situation is analogous to walking toward the center of the merry-go-round. Therefore, the ball will be deflected in the direction of Earth's rotation—that is, to the east.



NASA/Jeff Schmaltz, MODIS Land Rapid Response Team

Figure 9-15 Hurricanes in the Northern Hemisphere turn counterclockwise, as seen from above. This image of Hurricane Fran was taken from GEOS-8 less than seven hours before the eye went ashore at Cape Fear, North Carolina.



Earth is located in one of the spiral arms of the Milky Way Galaxy.

counterclockwise as viewed from above. The circulation pattern is reversed for hurricanes in the Southern Hemisphere and for high-pressure regions in the Northern Hemisphere. Figure 9-15 shows a hurricane in the Northern Hemisphere as seen from one of NASA's satellites. Folklore has it that the Coriolis force causes toilets and bathtubs to drain counterclockwise in the Northern Hemisphere, but its effects on this scale are so small that other effects dominate.

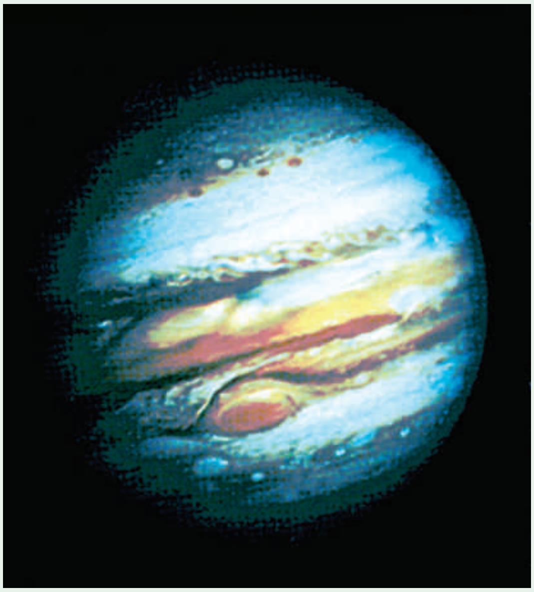
Even if Earth were not rotating, it would still not be an inertial reference system. Although Earth's orbital velocity is very large, the change in its velocity each second is small. The acceleration due to its orbit around the Sun is about one-sixth that of its daily rotation on its axis. In addition, the solar system orbits the center of the Milky Way Galaxy once every 250 million years with an average speed of 1 million kilometers per hour. The associated inertial forces are smaller than those due to rotation by a factor of about 100 million. The Milky Way Galaxy has an acceleration within the local group of galaxies, and so on.

In terms of our daily lives, Earth is very nearly an inertial reference system. Any system that is moving at a constant velocity relative to its surface is, for most practical purposes, an inertial reference system.

Everyday Physics | *Planetary Cyclones*

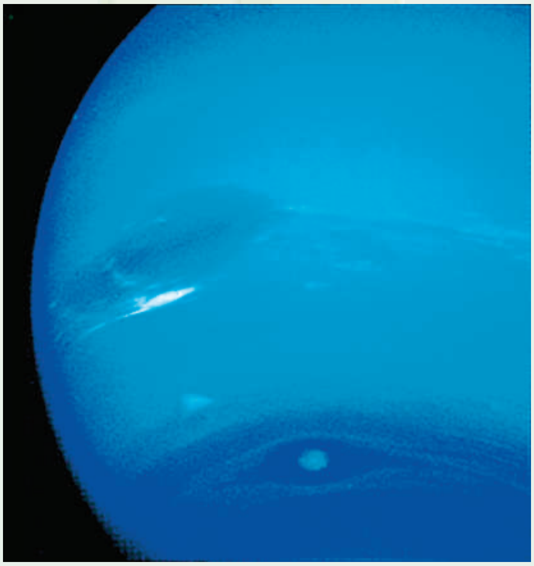
The atmospheres of the gaseous planets—Jupiter, Saturn, Uranus, and Neptune—are very unlike Earth's atmosphere. The atmospheres are composed primarily of hydrogen molecules with a much smaller amount of helium. All other gases constitute less than 1% of the atmospheres. Yet the colors provided by these gases (for instance, the clouds on Jupiter and Saturn are composed of crystals of frozen ammonia, and those on Uranus and Neptune are composed of frozen methane) give us some visual clues about the effects of the Coriolis force on the large-scale motions in these planetary atmospheres.

The most famous cyclone in the solar system is the Great Red Spot on Jupiter, which was first observed more than 300 years ago. It is a giant, reddish oval that is about 26,000 kilometers across the long dimensions—about the size of two Earths side by side. Because the Great Red Spot is located in Jupiter's southern hemisphere, we may expect it to rotate clockwise. However, it rotates *counterclockwise* with a period of 6 days. Therefore, the Coriolis effect tells us that the Great Red Spot must be a high-pressure storm rather than the low-pressure regions typical of hurricanes and cyclones on Earth. Jupiter also has three white ovals that were first observed in 1938 and have diameters of about 10,000 kilometers.



NASA

The Great Red Spot on Jupiter is a high-pressure cyclonic storm that has lasted for at least 300 years.



NASA

***Voyager 2* discovered this Great Dark Spot on Neptune during its flyby in the fall of 1989.**

When *Voyager 2* flew by Neptune in the fall of 1989, planetary scientists were surprised and pleased to observe a Great Dark Spot. It is located in Neptune's southern hemisphere, is about 10,000 kilometers across, and rotates counterclockwise with a period of 17 days. *Voyager* also observed a few small storms on the order of 5000 kilometers across in Saturn's atmosphere but none in Uranus's atmosphere.

Although no one knows the origins of these planetary storms, scientists can explain their long lives. Hurricanes on Earth die out rather quickly when they travel across land areas. Although each of these planets has a "rocky" core, the cores are relatively small compared to the planet's size. The resultant thickness of the atmospheres contributes to the long lifetimes of the storms. Another factor is size. Larger storms are more stable and last longer.

1. What evidence suggests that the Great Red Spot on Jupiter has higher pressure than the region surrounding it?
2. Is the Great Dark Spot on Neptune a high-pressure storm or a low-pressure storm? Explain how you can tell.

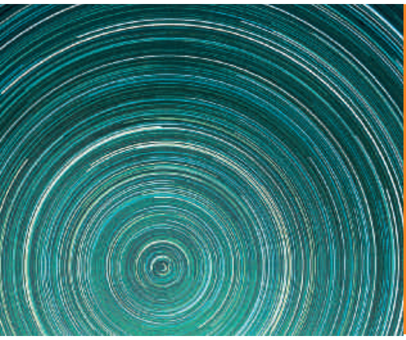
Summary

All motion is viewed relative to some reference system, the most common being Earth. An inertial reference system is one in which the law of inertia (Newton's first law) is valid. Any reference system that has a constant velocity relative to an inertial reference system is also an inertial reference system.

The Galilean principle of relativity states that the laws of motion are the same for any two inertial reference systems. Observers moving relative to each other report different descriptions for the motion of an object, but the objects obey the same laws of motion regardless of reference system.

Observers in different reference systems can reconcile the different velocities they obtain for an object by adding the relative velocity of the reference systems to that of the object. However, this procedure breaks down for speeds near that of light.

In a reference system accelerating relative to an inertial reference system, the law of inertia does not work without the introduction of fictitious forces that are due entirely to the accelerated motion. Centrifugal and Coriolis forces arise in rotating reference systems and are examples of inertial forces. Earth is a noninertial reference system, but its accelerations are so small that we often consider Earth an inertial reference system.



CHAPTER 9 *Revisited*

The most direct evidence of Earth's motion is provided by the Foucault pendulum. The plane in which the pendulum swings stays fixed relative to the distant stars and rotates relative to the ground, demonstrating that Earth is rotating. The effect of the Coriolis force on storm systems is also evident. This force occurs only in a rotating system and causes hurricanes to rotate in opposite directions on either side of the equator.

Key Terms

centrifugal force A fictitious force arising when a reference system rotates (or changes direction). It points away from the center, in the direction opposite the centripetal acceleration.

Coriolis force A fictitious force that occurs in rotating reference systems. It is responsible for the direction of winds in hurricanes.

Galilean principle of relativity The laws of motion are the same in all inertial reference systems.

geocentric model A model of the universe with Earth at its center.

heliocentric model A model of the universe with the Sun at its center.

inertial force A fictitious force that arises in accelerating (noninertial) reference systems. Examples are the centrifugal and Coriolis forces.

inertial reference system Any reference system in which the law of inertia (Newton's first law of motion) is valid.

noninertial reference system Any reference system in which the law of inertia (Newton's first law of motion) is not valid. An accelerating reference system is noninertial.

reference system A collection of objects not moving relative to each other that can be used to describe the motion of other objects. See *inertial reference system* and *noninertial reference system.*

Questions and exercises are paired so that most odd-numbered are followed by a similar even-numbered.
Blue-numbered questions and exercises are answered in Appendix B.
indicates more challenging questions and exercises.
WebAssign Many Conceptual Questions and Exercises for this chapter may be assigned online at WebAssign.

Conceptual Questions

1. Newton's first law states, "Every object remains at rest or in motion in a straight line at constant speed unless acted on by an unbalanced force." Is this "law" true in all reference frames? Explain.

2. Newton's third law states, "If an object exerts a force on a second object, the second object exerts an equal force back on the first object." Is this "law" true in all reference frames? Explain.

3. *Alice's Adventures in Wonderland* begins with Alice falling down a deep, deep rabbit hole. As she falls, she notices that the hole is lined with shelves and grabs a jar of orange marmalade. Upon discovering that the jar is empty, she tries to set it back on a shelf—a difficult task while she is falling. She is afraid to drop the jar because it might hit somebody on the head. What would really happen to the jar if Alice dropped it? Describe its motion from Alice's reference system and from the reference system of someone sitting on a shelf on the hole's wall.

4. Imagine riding in a glass-walled elevator that goes up the outside of a tall building at a constant speed of 20 meters per second. As you pass a window washer, he throws a ball upward at a speed of 20 meters per second. Assume, furthermore, that you drop a ball out a window at the same instant.
   a. Describe the motion of each ball from the point of view of the window washer.
   b. Describe the motion of each ball as you perceive it from the reference system of the elevator.

5. You wake up in a windowless room on a train, which rides along particularly smooth, straight tracks. Imagine that you have a collection of objects and measuring devices in your room. What experiment could you do to determine whether the train is stopped at a station or moving horizontally at a constant velocity?

6. Assume that you are riding on a windowless train on perfectly smooth, straight tracks. Imagine that you have a collection of objects and measuring devices on the train. What experiment could you do to determine whether the train is moving horizontally at a constant velocity or is speeding up?

7. The woman riding the train in the figure below drops a ball directly above a white spot on the floor. Where will the ball land relative to the white spot? Explain.

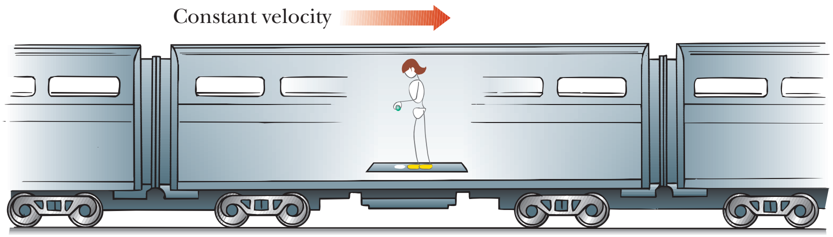
8. How would the woman in the figure below describe the ball's horizontal velocity while the ball is falling? Would an observer on the ground standing next to the tracks agree? Explain.

9. What would the woman in the figure below say about the horizontal forces acting on the ball as it falls? Would an observer on the ground standing next to the tracks agree? Explain.

10. What value would the woman in the figure below obtain for the acceleration of the ball as it falls? Would an observer on the ground standing next to the tracks obtain the same value? Explain.

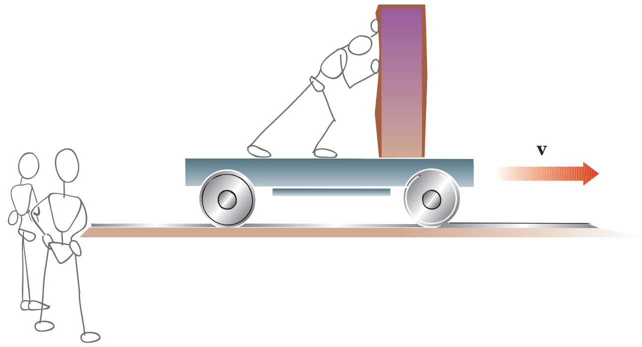
11. Would the woman and the observer on the ground in the figure below agree on the ball's kinetic energy just before it leaves her hand? Would they agree on the *change* in kinetic energy of the ball from the moment it leaves her hand until just before it hits the floor? Explain.

12. Would the woman and the observer on the ground in the figure below agree on the ball's momentum just before it leaves her hand? Would they agree on the *change* in momentum of the ball from the moment it leaves her hand until just before it hits the floor? Explain.



Questions 7–12. A train is traveling along a straight, horizontal track at a constant velocity of 50 kilometers per hour. An observer on the train holds a ball directly over a white spot on the floor of the train and drops it.

13. Gary is riding on a flatbed railway car, which is moving along a straight track at a constant 20 meters per second. Applying a 600-newton force, Gary is trying in vain to push a large block toward the front of the car. His two friends, Cindy and Mitch, are watching from beside the track. Would Gary and Cindy agree on the value of the block's kinetic energy at the instant Gary passes his friends? Would they agree on the *change* in the block's kinetic energy in the next second? Explain.



14. Mitch, in Question 13, has just returned from physics class where he was studying about work. Mitch argues that, from his frame of reference, Gary applies a 600-newton force for a distance of 20 meters in 1 second and therefore does 12,000 joules of work on the block. He wonders why the block does not appear to speed up as a result of this work. What is the flaw in Mitch's reasoning?

15. Assume that you are driving down a straight road at a constant speed. A small ball is tied to a string hanging from the rearview mirror. Which way will the ball swing when you apply the brakes? Explain your reasoning.

16. Assume that you are driving down a straight road at a constant speed. A helium-filled balloon is tied to a string that is pinned to the front seat. Which way will the balloon swing when you apply the brakes? Explain your reasoning.

17. If the train in the figure below is traveling to the right, is it speeding up or slowing down? What if it is traveling to the left?

18. If all the curtains on the train in the figure below were closed, what experiment (if any) could the woman perform to determine whether the train was traveling to the right or to the left? Explain.

19. The woman riding the train in the figure below drops a ball directly above a white spot on the floor. Where will the ball land relative to the white spot? Why doesn't it matter whether the train is moving to the right or to the left?

20. The woman on the train in the figure below observes that the ball falls in a straight line that is slanted away from her. Is the magnitude of the ball's acceleration along this line greater than, equal to, or less than the usual acceleration due to gravity? Explain.

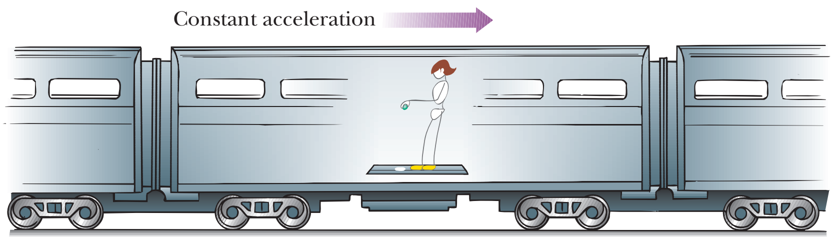
21. How would the woman in the figure below describe the ball's horizontal velocity both just after releasing the ball and just before it strikes the floor of the train? Explain.

22. What would an observer on the ground obtain for the horizontal speed of the ball in the figure below right after the ball is released and right before it hits the floor of the train? Explain.

23. What would the woman in the figure below say about the horizontal forces acting on the ball as it falls? Would an observer on the ground standing next to the tracks agree? Explain.

24. Draw the free-body diagram for the falling ball in the figure below from the reference frame of the woman on the train. For each force on the diagram, state, if possible, the object responsible for the force. Repeat this from the reference frame of the observer on the ground.

25. A 180-pound person takes a ride in the elevator that goes up the side of the Space Needle in Seattle. Much to the amusement of the other passengers, this person stands on a bathroom scale during the ride. During the time the elevator is accelerating upward, is the reading on the scale greater than, equal to, or less than 180 pounds? Explain.



Questions 17–24. A train is traveling along a straight, horizontal track with a constant acceleration as indicated. An observer on the train holds a ball directly over a white spot on the floor of the train. At the instant the speed is 50 kilometers per hour, she drops the ball.

26. During the time the elevator in Question 25 is moving upward with a constant speed, is the reading on the scale greater than, equal to, or less than 180 pounds? Explain.

27. Assume you are standing on a bathroom scale while an elevator slows down to stop at the top floor. Will the reading on the scale be greater than, equal to, or less than the reading after the elevator stops? Why?

28. The elevator in Question 27 now starts downward to return to the ground floor. Will the reading on the scale be greater than, equal to, or less than the reading with the elevator stopped? Why?

29. If a child weighs 200 newtons standing at rest on Earth, would her apparent weight be less than, equal to, or more than 200 newtons if she were in a spaceship accelerating at 10 (meters per second) per second in a region of space far from any celestial objects? Why?

30. The child in Question 29 enters a circular orbit at constant speed around a distant planet. The spacecraft's centripetal acceleration is 10 (meters per second) per second. Would her apparent weight be less than, equal to, or more than 200 newtons? Why?

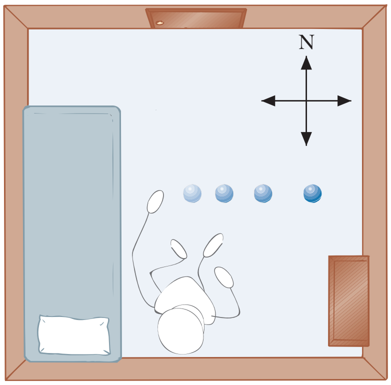
31. If you were allowed to leave your tray down while your DC-9 accelerates for takeoff, why would objects slide off the tray?

32. What happens to the surface of a drink if you hold the drink while your Boeing 777 accelerates down the runway?

33. Assume that a meter-stick balance is balanced with a 20-gram mass at 40 centimeters from the center and a 40-gram mass at 20 centimeters from the center. Will it remain balanced if it is in an elevator accelerating downward? Explain your reasoning.

34. Assume that you weigh a book on an equal-arm balance while an elevator is stopped at the ground floor. Would you get the same result if the elevator were accelerating upward? Explain your reasoning.

35. You wake up in a windowless room on a train, traveling along particularly smooth, horizontal tracks. You don't know in which direction the train is moving, but you are carrying a compass. You place a ball in the center of the floor and observe as it rolls east. If the train is moving west, is it speeding up, slowing down, or turning with constant speed? (If turning, state right or left.) What if it is moving east? Explain.



36. Consider the train in Question 35. If the train is moving north, is it speeding up, slowing down, or turning with constant speed? (If turning, state right or left.) What if it is moving south? Explain.

37. In an inertial reference system, we define *up* as the direction opposite the gravitational force. In a noninertial reference system, *up* is defined as the direction opposite the vector sum of the gravitational force and any inertial forces. Which direction is up in each of the following cases?

  a. An elevator accelerates downward with an acceleration smaller than that of free fall.
  b. An elevator accelerates upward with an acceleration larger than that of free fall.
  c. An elevator accelerates downward with an acceleration larger than that of free fall.

38. Using the definition of *up* in Question 37, which direction is up for each of the following situations?

  a. A child rides near the outer edge of a merry-go-round.
  b. A train's dining car going around a curve turns to the right.
  c. A skier skis down a hill with virtually no friction.

39. Which direction is up for astronauts orbiting Earth in a space shuttle?

NASA

40. What happened to the astronauts' sense of up and down as the *Apollo* spacecraft passed the point in space where the gravitational forces of Earth and the Moon are equal? Explain.

41. You and a friend are rolling marbles across a horizontal table in the back of a moving van traveling along a straight section of an interstate highway. You roll the marbles toward the side of the van. What can you say about the velocity and acceleration of the van if you observe the marbles (a) head straight for the wall? (b) Curve toward the front of the van?

42. A ball is thrown vertically upward from the center of a moving railroad flatcar. Where, relative to the center of the car, does the ball land in each of the following cases?

  a. The flatcar moves at a constant velocity.
  b. The velocity of the flatcar increases.
  c. The velocity of the flatcar decreases.
  d. The flatcar travels to the right in a circle at constant speed.

Blue-numbered answered in Appendix B = more challenging questions

43. You fill a bucket half full of water and swing it in a vertical circle. When the bucket is at the top of its arc, the bucket is upside down but the water does not spill on your head. What direction is "up" for the water? Explain.

44. Would it be possible to take a drink at the top of a loop-the-loop on a roller coaster? Explain.

45. For a science project, a student plants some bean seeds in water and lets them grow in containers fastened near the outer edge of a merry-go-round that is continually turning. Draw a side view of the experiment showing the direction in which the plants will grow.

46. A student carries a ball on a string onto the rotating cylinder ride shown in Figure 9-9. With the ride in operation, she holds her hand straight in front of her and lets the ball hang by the string. Using a side view, draw a free-body diagram for the ball from the student's reference frame. For each force on the diagram, state, if possible, the object responsible for the force.

47. Why does the mud fly off the tires of a pickup traveling down the interstate?

48. The Red Cross uses centrifuges to separate the various components of donated blood. The centrifugal force causes the denser component (the red blood cells) to go to the bottom of the test tube. If there were a dial on the wall of the lab that allowed the "local gravity" to be increased to any value, would the centrifuge still be required? Why or why not?

49. Copernicus had difficulty convincing his peers of the validity of his heliocentric model because if Earth were moving around the Sun, stellar parallax should have been observed, which it wasn't. If Earth's orbital radius about the Sun were magically doubled, would this make stellar parallax easier or harder to observe? Explain.

50. Assuming that Earth is a perfect sphere and that the gravitational field has a constant magnitude at all points on the surface, would your apparent weight at the equator be greater than, smaller than, or the same as at the North Pole?

51. Would a Foucault pendulum rotate at the equator? Explain your reasoning.

52. If you set up a Foucault pendulum at the South Pole, would it appear to rotate clockwise or counterclockwise when viewed from above? Why?

53. Why are there no hurricanes on the equator?

54. In preparation for hunting season, you practice at a shooting range in which the targets are located straight to the south. You find that you must aim slightly to the right of the target to account for the Coriolis force. Are you in the Northern or the Southern Hemisphere? If you are out hunting and shoot to the north, do you have to aim slightly to the right or slightly to the left to ensure a direct hit? Explain your reasoning.

Exercises

55. A spring gun fires a ball horizontally at 15 m/s. It is mounted on a flatcar moving in a straight line at 25 m/s. Relative to the ground, what is the horizontal speed of the ball when the gun is aimed (a) forward? (b) Backward?

56. An aircraft carrier is moving to the north at a constant 25 mph on a windless day. A plane requires a speed relative to the air of 125 mph to take off. How fast must the plane be traveling relative to the deck of the aircraft carrier to take off if the plane is headed (a) north? (b) South?

57. A child can throw a ball at a speed of 50 mph. If the child is riding in a bus traveling at 20 mph, what is the speed of the ball relative to the ground if the ball is thrown (a) forward? (b) Backward?

58. A transport plane with a large rear-facing cargo door flies at a constant horizontal speed of 400 mph. A major-league baseball pitcher hurls his best fastball, which he throws at 95 mph, out the rear door of the plane. Describe what the motion of the baseball would look like to an observer on the ground.

59. What would an observer measure for the magnitude and direction of the free-fall acceleration in an elevator near the surface of Earth if the elevator (a) accelerates downward at 6 m/s^2? (b) Accelerates downward at 16 m/s^2?

60. An observer measures the free-fall acceleration in an elevator near the surface of Earth. What would the value and direction be if the elevator (a) accelerates upward at 4 m/s^2? (b) Travels upward with a constant speed of 4 m/s?

61. A person riding a train at a constant speed of 30 m/s drops a 2-kg backpack from a height of 1.25 m. The fall requires half a second and the backpack acquires a vertical velocity of 5 m/s. Find the initial kinetic energy, the final kinetic energy, and the change in kinetic energy from the reference system of an observer on the train.

62. Consider the falling backpack described in Exercise 61 from the reference system of an observer standing along the side of the track. Find the initial kinetic energy, the final kinetic energy, and the change in kinetic energy. How do the changes in kinetic energy compare in the two cases?

63. What is the maximum total force exerted on a 50-kg astronaut by her seat during the launch of a space shuttle?

64. What would be the maximum total force exerted on a 90-kg fighter pilot when ejecting from an aircraft?

65. A child weighs 300 N standing on Earth. What is the apparent weight of the child in an elevator accelerating upward at 0.3 g?

66. An elevator is moving downward and slowing down with an acceleration of 0.1 g. If a person who weighs 800 N when at rest on Earth steps on a bathroom scale in this elevator, what will the scale read?

67. An 8-kg monkey rides on a bathroom scale in an elevator that is accelerating upward at $\frac{1}{4}$ g. What does the scale read?

68. What does the scale read if a 5-kg cat lies on a bathroom scale in an elevator accelerating downward at 0.2 g?

69. A room is being accelerated through space at 3 m/s^2 relative to the "fixed stars." It is far from any massive objects. If a man weighs 800 N when he is at rest on Earth, what is his apparent weight in the room?

70. A woman with a weight of 700 N on Earth is in a spacecraft accelerating through space a long way from any massive objects. If the acceleration is 4 m/s^2, what is her apparent weight in the ship?

71. A cylindrical space station with a 40-m radius is rotating so that points on the walls have speeds of 20 m/s. What is the acceleration due to this artificial gravity at the walls?

72. What is the centrifugal acceleration on the equator of Mars given that it has a radius of 3400 km and a rotational period of 24.6 h? How does this compare to the acceleration due to gravity on Mars of 3.7 m/s^2?

10

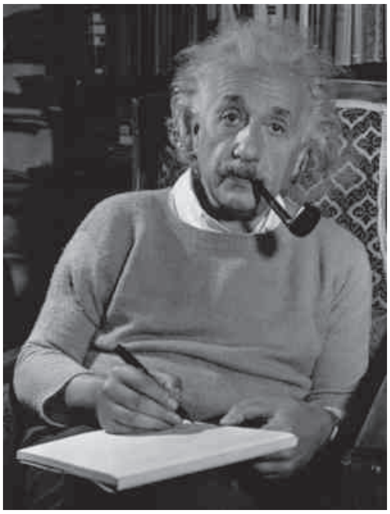
Einstein's Relativity

▶At various times in our lives, we have all had impressions of the passage of time. An hour in a dentist's chair seems much longer than 2 hours watching a good movie. But what is time? If we develop a foolproof way of measuring time, will all observers in the universe accept our measurements?

(See page 209 for the answer to this question.)

Telegraph Colour Library/Taxi/Getty Images

Time and space are central in the theories of special and general relativity, and they take on new roles.



© Lucien Aigner/CORBIS

Albert Einstein (1879–1955)

WHEN observers in different inertial reference systems describe the same events, their reports don't match. In the framework of classical relativity, they disagree in their descriptions of the paths and on the values of an object's velocity, momentum, and kinetic energy. On the other hand, they agree on relative positions, lengths, time intervals, accelerations, masses, and forces. Even the laws of motion and the conservation laws are the same.

We never asked, or even thought to ask, whether some of these were actually the same for all reference systems or whether we had just assumed them to be the same. In classical relativity we assumed that the concepts of length, time, and mass were the same. But are they really the same?

Albert Einstein asked this question. He reexamined the process of describing events from different reference systems with an emphasis on the concepts of space and time. This led to the development of the **special theory of relativity**.

Einstein arrived at the special theory of relativity by setting forth two *postulates*, or conditions, that were assumed to be true. He then examined the effects of these postulates on our basic concepts of space and time. The predictions of special relativity were then compared with actual experimental measurements. The theory had to agree with nature to have any validity.

The First Postulate

The **first postulate of special relativity** is related to the question of whether there exists an absolute space—some signpost in the universe from which all motion can be regarded as absolute. This postulate says that there is no absolute space; any inertial reference system is just as good as any other. Einstein's first postulate is a reaffirmation of the Galilean principle of relativity.

first postulate of special relativity ▶

The laws of physics are the same in all inertial systems.

As we discussed in the previous chapter, Galileo argued that a traveler in the hold of a ship moving with a constant velocity could not conduct experiments that would determine whether the ship was moving or at rest. However, the Galilean principle of relativity came into question near the end of the 19th century. A theory by Scottish physicist James Clerk Maxwell describing the behavior of electromagnetic waves, such as light and radio, yielded unexpected results.

In Newton's laws, reference systems moving at constant velocities are equivalent to each other. If, however, one system accelerates relative to another, the systems are not equivalent. Because Newton's laws depend on acceleration and not on velocity, acceleration of a reference system can be detected, but its velocity cannot.

In Maxwell's theory, however, the *velocity* of the electromagnetic waves appears in the equations rather than their acceleration. According to the classical ideas, the appearance of a velocity indicated that inertial systems were not equivalent. In principle you could merely turn on a flashlight and measure the speed of light to determine how your reference system was moving.

Maxwell's equations and the Galilean principle of relativity were apparently in conflict. It seemed that the physics world view could not accommodate both. During his studies, Einstein developed a firm belief that the principle of relativity must be a fundamental part of any physical theory. At the same time, he wasn't ready to abandon Maxwell's new ideas about light. He felt that the conflict could be resolved and that both the principle of relativity and Maxwell's equations could be retained.

Meanwhile, others were pursuing different options. If there were an absolute reference system in the universe, it should be possible to find it. The key seemed to lie in the behavior of light.

Searching for the Medium of Light

◀ Extended presentation available in the *Problem Solving* supplement

Although it was well established in the late 1800s that light was a wave phenomenon, nobody knew what substance was waving. Sound waves move by vibrating the air, ocean waves vibrate water, and waves on a rope vibrate the rope. What did light vibrate? It was assumed that there must be some medium through which light traveled. This medium was called the **ether**.

But if space were filled with such a medium, it should be detectable. From their knowledge of the behavior of other waves, scientists were convinced that the ether had to be fairly rigid. Therefore, as Earth passed through this ether in its annual journey around the Sun, it should be slowed by friction. However, no such slowing was detected. How could the ether be rigid and yet so intangible that Earth could pass through it without slowing?

Two American physicists, A. A. Michelson and E. W. Morley, tried to detect the ether with an experiment that raced two light beams in perpendicular directions, as shown in Figure 10-1. They reasoned that Earth's annual motion around the Sun should create an ether "wind" on Earth, much as a moving car creates a wind for the passengers. This ether wind would affect the speed of light differently along the two paths, and the race would not end in a tie. They calculated that their experiment was sensitive enough to measure a speed relative to the ether as small as one-hundredth of Earth's orbital speed. Although the experiment was conducted at many times of the year and in many different orientations, the results were always the same—every race ended in a tie!

Not finding the ether wind with such a straightforward experiment was shocking. Physicists were receiving conflicting information. First, there *must* be an ether wind; second, there *must not* be an ether wind. The problem was in the first message: light does not require a medium. It can travel through a vacuum. It is a wave that doesn't wave anything.

The Second Postulate

It is difficult (if not impossible) to re-create a creative process. Although Einstein mentioned the failure to find the ether in his 1905 paper, years later he indicated that his primary motivation in formulating the **second postulate of**

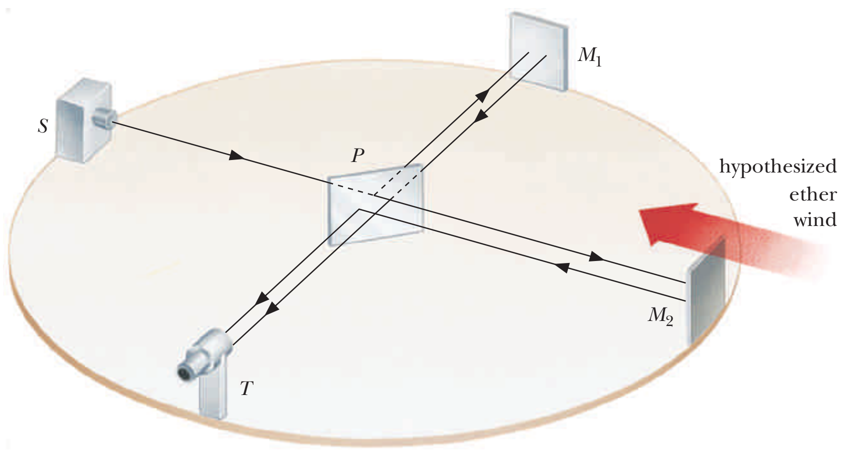


Figure 10-1 A race between two light beams in perpendicular directions was supposed to detect the hypothesized ether. In this experiment a light beam from the source *S* is split by the partially silvered mirror *P* and travels two different paths to the telescope *T*.

special relativity was his deep belief in the principle of relativity. He could reconcile the apparent contradiction between the principle of relativity and Maxwell's equations with his second postulate because it eliminated the possibility of using the speed of light to distinguish between inertial reference systems.

second postulate of special relativity ▶

The speed of light in a vacuum is a constant regardless of the speed of the source or the speed of the observer.

At first glance the second postulate may seem to be a rather innocent statement. But consider the situation of your friends in the van from the previous chapter. We agreed that the velocity of an object measured relative to the ground was different from the velocity measured relative to the van—the difference depended on how fast the van was moving relative to the ground. Einstein's second postulate says that this doesn't happen with light.

If your friends move toward us and turn on a flashlight, we may expect that we would measure the speed of light to be greater than that from a flashlight on the ground. We find, however, that we get the same speed. It doesn't matter that the flashlight is moving relative to us. Even if we moved very rapidly toward the flashlight, the results would be the same. Regardless of any relative motion, any measurement of the speed of light yields the same value: 300,000 kilometers per second (186,000 miles per second).

Q: If we were communicating with an alien spaceship approaching Earth at 20% the speed of light, at what speed would we receive their signals, and at what speed would they receive ours?

A: Because radio and light behave the same, it would not matter which type of signal we used. In either case the second postulate tells us that both observers would receive the signals at the speed of light, not at 120% of this speed, as would be predicted intuitively.

Simultaneous Events

When Einstein's two postulates are applied to rather simple measurements, unexpected consequences occur. Consider the question of determining whether two events took place at the same time. How would we know, for example, if two explosions happened simultaneously? We all have an intuitive feeling about this and don't usually even think to question it. Einstein cautioned that we must not simply accept this intuitive feeling. We should look carefully at how we determine the validity of such statements.

To determine the simultaneity of two events, we must receive some type of signal indicating that each event occurred. To be specific, let's determine whether two paint cans exploded at the same time. If the two cans are in the same place, as in Figure 10-2, we can agree that they exploded simultaneously if the light signals from the two explosions arrived together. The signals traveled the same distance, and their simultaneous arrival means that the explosions occurred at the same time. The simultaneity of events at a single location does not present a problem.

If the paint cans are not in the same place, we have to be more careful. The signals could arrive together even though the explosions occurred at different times. The results depend on the distances to each explosion. Clearly, the easiest case occurs when the observer is the same distance from each event;

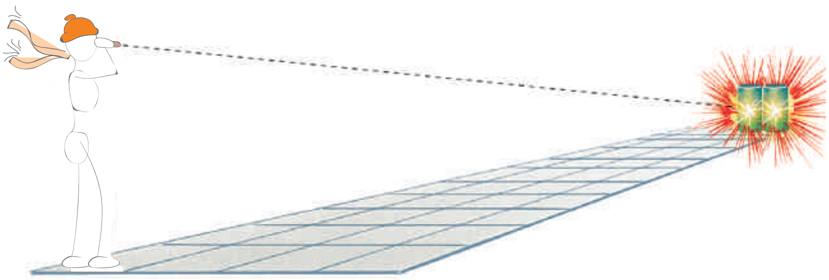


Figure 10-2 The simultaneity of events at a single location presents no problem.

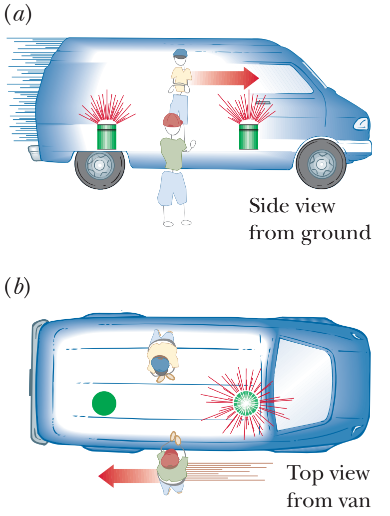


Figure 10-3 (a) The paint cans explode when they are equal distances from each observer. Although the ground observer claims that the events were simultaneous, the observer in the van (b) claims that the can on the right exploded first.

then the simultaneous arrival of the signals indicates that the events occurred simultaneously.

Einstein had no quarrel with this method of determining simultaneity. His concern was whether *all* observers would agree on the simultaneity; he concluded that they wouldn't. He claimed that two observers moving relative to each other at a constant velocity cannot agree on whether two events happen at the same time. This statement probably seems incredible. You may say, "How can two people see the same physical events and disagree on their simultaneity? They really did happen at the same time . . . didn't they?"

Einstein would say that there is no such thing as universal agreement about simultaneity. To understand this, let's return to your friends in the van. Assume that the paint cans are located equal distances to the right and left of one of your friends and that the van is moving with constant velocity to the right relative to you on the ground. Assume that, at the moment when you were also equal distances from the paint cans, the cans exploded, as shown in Figure 10-3(a). You know that they exploded simultaneously because the signals arrived at your eyes simultaneously, and you can verify that you are equal distances from the paint marks on the ground.

How would this apply to one of your friends in the van? During the time it took the signals to reach him, he approached the right-hand signal and receded from the left-hand one, as shown in Figure 10-3(b). The signal from the right-hand explosion therefore reached his eyes before the left-hand one. Both of you agree that the arrival of the signals at his eyes was not simultaneous.

Q: Why do you both agree that the signals arrived at your friend's eyes at different times?

A: Different observers agree on the simultaneity (or nonsimultaneity) of events at a single location—in this case, at your friend's eyes.

Your friend concludes that the explosions were not simultaneous. He reports, "I'm standing here in the middle of the van. I can tell by the paint marks on the floor of the van that the explosions happened equal distances from me, but the signals did not reach my eyes simultaneously. Clearly, the one that reached me first came from the explosion that happened first."

"Well," you may counter, "I understand why you think that. You were moving and that's why you reached a different conclusion."

"I'm not moving!" retorts your friend.

According to the first postulate, his motion is no more certain than yours. From his point of view, he is standing still, and you are moving. There is nothing either of you can do to determine who is *really* moving. From his point simultaneity is relative ▶

of view, *you* falsely concluded that the events were simultaneous because *you* moved to the left and thus shortened the distance that the left-hand signal traveled to your eyes.

How do we get ourselves out of this predicament? Einstein concluded that we don't. You and your friend are both correct. You each believe that you have the correct answer and that the other is moving and therefore has been fooled. There is no way to resolve the conflict other than to admit that simultaneity is relative.

FLAWED REASONING

Your friend says, "I don't see why special relativity is so special. It is obvious that two events can be simultaneous for one person and not for another. For example, if I am camped exactly halfway between volcano A and volcano B and hear them both erupt at exactly the same time, someone camped closer to volcano A would hear it erupt first. The difference is just the time delay for the sound to travel the greater distance."

Your friend is just not seeing the big picture. **What is the error in your friend's thinking?**

ANSWER Special relativity predicts that events that are simultaneous in one reference system may not be simultaneous in another. This is much more fundamental than time delays due to signal speed. The camper closer to volcano A could calculate the time required for the sound to travel from each volcano and determine that they must have erupted at the same time. This camper would agree with your friend about the simultaneity of the events, even though she heard the eruptions at different times. An observer flying past the volcanoes in a spaceship, however, would do the same calculation and determine that they did not erupt simultaneously.

Synchronizing Clocks

Because our concepts of motion are fundamental to the physics world view, disagreements in simultaneity could result in a radical revision. For example, when we discussed the motion of a ball and talked about the ball being 20 meters above the ground at a time of 3 seconds, we were claiming that the ball was at this position at the same instant that the hands on the clock indicated 3 seconds. That is, the two events occurred simultaneously.

Remember that disagreements only occur when the events are at different locations. Rather than trying to determine distant events with a single clock located near you, you could set up a series of clocks distributed throughout space. Then each event could be recorded on a clock at that location, and there would be no problem with the simultaneity of the event and the clock reading.

However, for this to work, all the clocks must be synchronized. But how do we know that they are synchronized? Even if they are synchronized in one reference system, will they be synchronized in all inertial reference systems?

To answer these questions, we need to examine the process of synchronizing clocks in different places. It may be tempting to suggest that we follow the procedure used for years in war movies. The soldiers rendezvous to synchronize their wristwatches and then disperse. Clearly, this method worked quite satisfactorily for them, but we have no guarantee that the watches remain synchronized. We don't know, for example, whether the motion of a clock affects its timekeeping ability.

One way of synchronizing separated clocks is illustrated in the sequence of strobe drawings in Figure 10-4. A flashbulb is mounted on top of a pole located midway between the two clocks. Initially, the clocks are preset to the same time and are not running. They are designed to start when light signals hit photocells mounted on their roofs. After the flash (a), the light expands in a sphere centered on the top of the pole (b and c). The light signals are detected as they arrive at each clock (d), starting the clocks simultaneously. The two clocks are now synchronized (e).

Let's now attempt to synchronize clocks in two different inertial systems. We assume that each system has the same setup as that used in Figure 10-4 and that the clocks are located along a line parallel to the direction of *relative* motion. Pretend you are located in the lower system of Figure 10-5 and see the upper system moving to the right with constant velocity. The flashbulb goes off as the two poles meet (b). You see the light expanding in a sphere about the pole in your inertial system (c). (It does not matter which bulb flashes, or even whether both flash, because you measure the speed of light to be a constant independent of the motion of the source.) Because you see the upper system moving to the right, the left-hand clock moves toward the light signal and starts first (d). The two clocks in your system start simultaneously (e). Notice, however, that it takes some additional time for the light signal to catch up with the right-hand clock (h) in the upper system, and it starts after the left-hand clock.

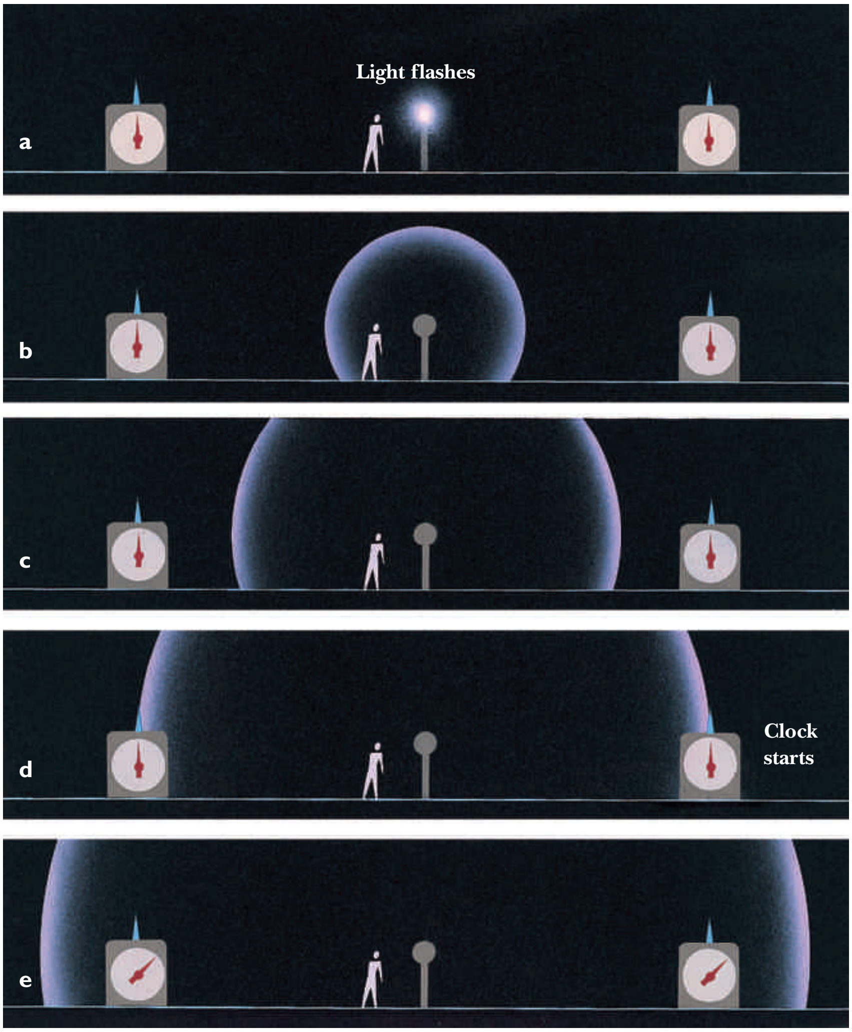
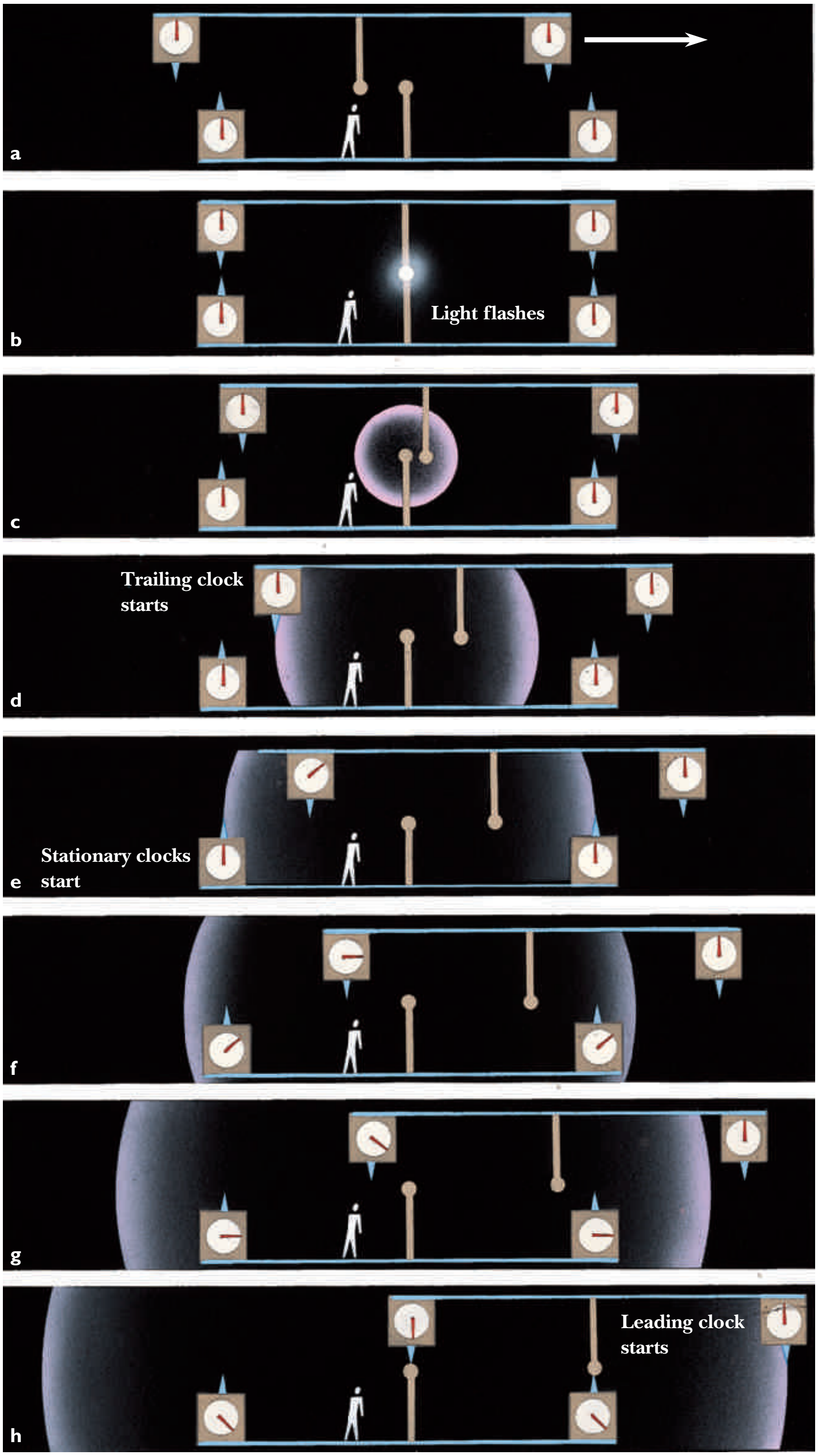


Figure 10-4 Strobe drawings illustrating a method of synchronizing two separated clocks in a single inertial system.

Figure 10-5 An attempt to synchronize clocks in two inertial systems as viewed by an observer in the lower system.



You report that your clocks are synchronized but that the clocks in the other system are not synchronized. Because the upper system was moving to the right during the time that the light signal was en route, the clock on the left moved toward the signal, while the one on the right moved away from it. You observe that the light traveled a shorter distance to the left-hand clock, and it was therefore started before the right-hand one.

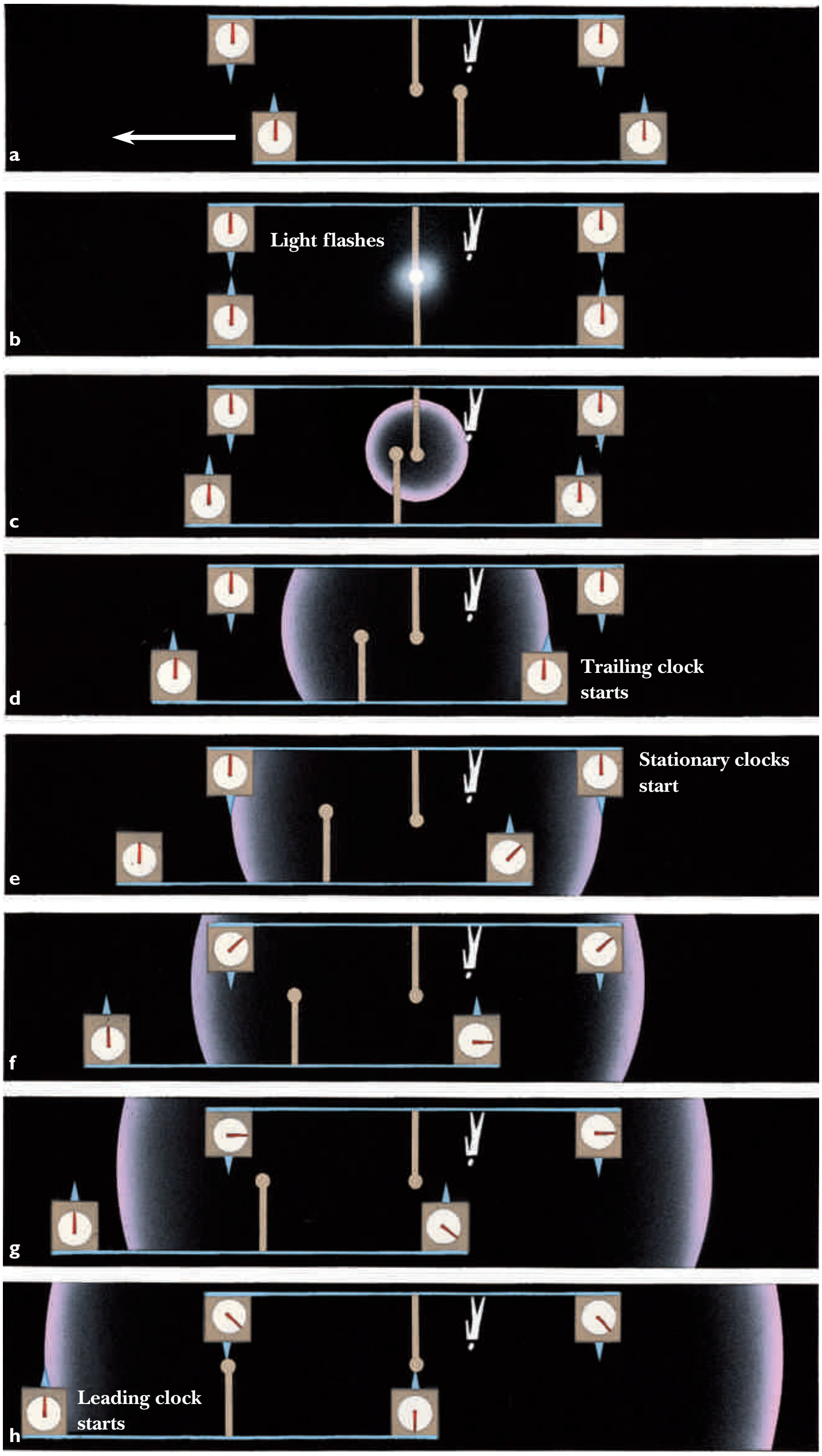


Figure 10-6 The same attempt to synchronize the clocks shown in Figure 10-5 but as viewed by an observer in the upper system.

What would the observer viewing the events from the other inertial system say? Let's repeat the analysis, assuming that you are now in the upper system. From this point of view, you observe the lower system moving to the left, as shown in Figure 10-6. Once again you see the light signal expand in a sphere centered on the top of the pole in your system (c). The two clocks in your system start simultaneously (e). You see the right-hand clock in the lower system approach the light signal and start first (d). Only later is the left-hand clock in the lower system started (h). You conclude that the clocks in your system are synchronized, but the clocks in the lower system are not synchronized.

All observers conclude that the clocks in their own reference system are synchronized and the clocks in all other reference systems are not synchronized. This conflict cannot be resolved. The first postulate says that the two inertial reference systems are equivalent; no experiments can be performed to determine which observer is "really" at rest.

The equivalence can be made more apparent by noting that in each case it was the trailing clock that moved toward the light signal and thus started early. We can summarize the situation by observing that the *trailing clocks lead.*

trailing clocks lead ▶

Q: A conductor on board a fast-moving train verifies that all clocks on the train are synchronized. What do observers on the ground say about this?

A: They find that the clock in the caboose is ahead of the clock in the engine.

Time Varies

Can observers in different inertial systems agree on the time interval between two events taking place at the same location and measured on the same clock? To examine this question, consider the unusual but legitimate clock shown in Figure 10-7. Clocks keep time by counting some regular cycle. In this clock the cycle is initiated by firing a flashbulb at the bottom. The light signal travels to the mirror at the top of the cylinder and is reflected downward. The photocell receiving the signal initiates a new cycle by firing the flashbulb again.

Imagine an identical clock in your friends' van. The light that strikes the top mirror and returns to the photocell must be that portion of the flash that left at an angle to the right of the vertical. Therefore, it travels the larger distance shown in Figure 10-8. Because the speed of light is a constant, the time for the round-trip must be longer. The time interval between flashes is longer for the moving clock; that is, time is dilated. The moving clock runs slower.

moving clocks run slower ▶

Your friends' report is different. The light signal in their clock travels straight up and down, whereas the signal in your clock takes the longer path. They claim that your time is dilated. Note that each of you agrees that moving clocks run slower. This equivalence is in agreement with the first postulate.

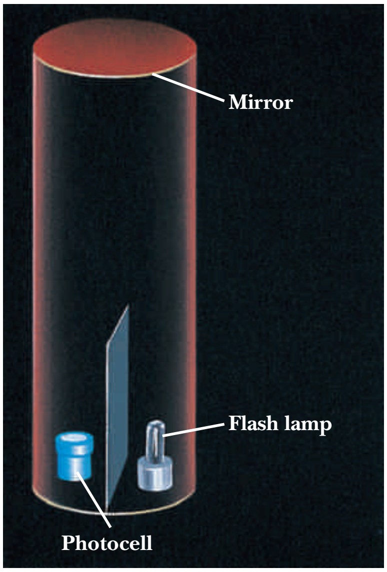


Figure 10-7 A light clock.

The implications of time dilation are startling. According to the first postulate, *all* clocks in the moving system must run at the same rate. This statement applies to physical, chemical, and even biological clocks. Thus, pulse rates will be lower, biological aging will be slower, the pitch of musical notes will be lower, and so on. Time itself changes when viewed from different inertial systems.

At first glance it may seem as though Einstein discovered the fountain of youth. If we traveled at a high velocity, clocks would run slower, and we would live longer. Unfortunately, this isn't the case. Within our own inertial system, everything is normal. Our biological clocks run at their normal pace, and we age normally. Nothing changes.

We should also note that we have not invented a time machine that will allow us to go back into history. Although we can make moving clocks run very slowly by giving them very high speeds, we cannot make them run backward. If this were possible, a person moving relative to you could conceivably see your death before your birth! Obviously, this would play havoc with our ideas of cause and effect.

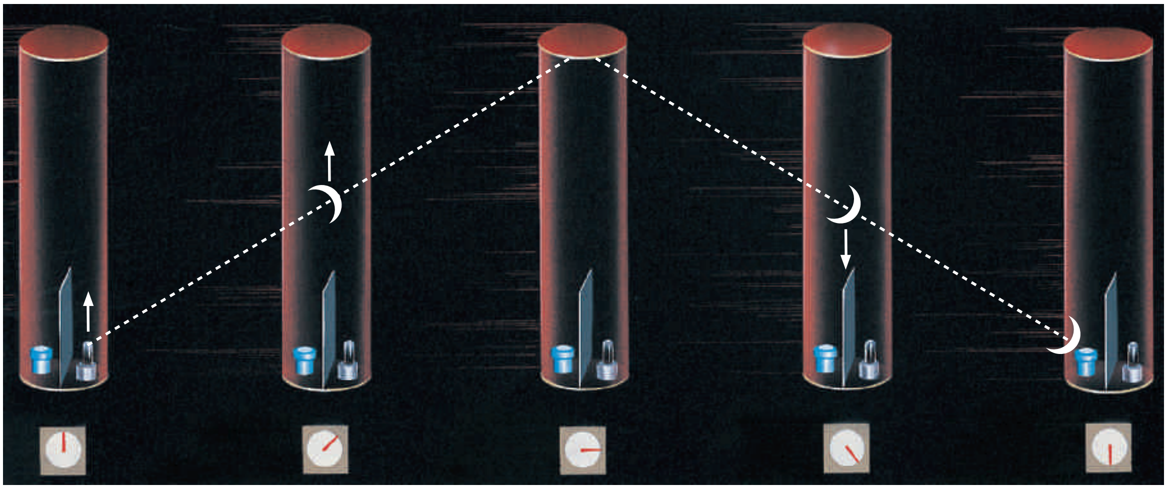


Figure 10-8 The light in the moving clock travels farther, and therefore the clock runs slower.

Q: Assume that both you and your friends are carrying clocks. If you determine that your friends' clock is running 10% slower, what will your friends say about your clock?

A: Because the first postulate requires the situations to be symmetric, your friends will observe your clock to be running 10% slower than theirs.

Experimental Evidence for Time Dilation

The size of the effects predicted by the special theory of relativity increases with speed. The time interval in the moving system is equal to the time interval in the rest system multiplied by an adjustment factor. The *relativistic adjustment* factor is called gamma (γ) and is given by

$$\gamma = \frac{1}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$

◀ relativistic adjustment factor

In this expression, v is the relative speed of the inertial systems, and c is the speed of light. Notice that the value of the adjustment factor depends only on the ratio of these speeds and always has a value greater than or equal to 1.

In Table 10-1 we have calculated the values for the adjustment factor for different speeds of the moving system. As you can see from the first two entries in the table, a clock moving at ordinary speeds relative to an observer is slowed by a seemingly negligible amount. For instance, a clock moving at three times the speed of sound would have to travel for 63 centuries before it lost 1 second relative to a clock at rest!

An experiment to detect the slowing of a clock during a transcontinental flight would need to detect differences of a few billionths of a second. However, modern atomic clocks are sensitive to such small time differences. Jet planes, each with several atomic cesium clocks, were flown in opposite directions around Earth. Two experiments—one in 1971 and one in 1977—confirmed the predictions.

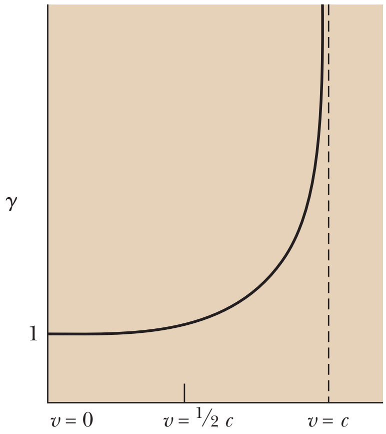


Figure 10-9 A graph of the adjustment factor versus the ratio of the speed of the system or object to the speed of light.

Table 10-1 *The Value of the Adjustment Factor for Various Speeds*

Speed	Adjustment Factor
The fastest subsonic jet plane	1.000 000 000 000 6
Three times the speed of sound	1.000 000 000 005
1% the speed of light	1.000 05
10% the speed of light	1.005
25% the speed of light	1.03
50% the speed of light	1.15
80% the speed of light	1.67
99% the speed of light	7.09
99.99% the speed of light	70.7
99.9999% the speed of light	707
The speed of light	Infinite

Figure 10-9, the graph of the adjustment factor versus speed, shows that the effects become infinitely large as the speed approaches that of light. An early verification of time dilation at these large speeds involved the behavior of subatomic particles known as *muons*. Muons are created high in our atmosphere by collisions of particles from outer space with air molecules. Time dilation can be tested with these fast-moving muons because they are radioactive; they spontaneously break up into other particles. This radioactive decay provides us with a simple but very accurate clock.

Q: Assuming that you could measure the radioactivity of muons flying past you, would you expect the muons to last for a longer or a shorter time because of the relativistic effects?

A: Because the muons are moving, their radioactive decays should be slowed as viewed from Earth. Therefore, they will last longer than if they were at rest in the laboratory or if you were moving along with them.

Knowing the number of muons present at a high elevation and the characteristics of the radioactive "clocks," one can predict quite accurately, in the absence of any relativistic effects, how many muons should reach Earth's surface before disintegrating. Experiments yielded a much greater number of muons at sea level than predicted. In fact, the number of muons agrees with calculations that assume that the decay time for the muons is dilated as predicted.

WORKING IT OUT *Relativistic Times*

Muons at rest in the laboratory have an average lifetime of 2.2 microseconds ($1\ \mu s = 10^{-6}$ s). This average lifetime is measured with a clock that is also at rest in the laboratory.

What is the average lifetime of muons traveling at 99% of the speed of light? According to Table 10-1, the adjustment factor for this speed is 7.09. Let's imagine a clock moving with the muons. This clock is at rest relative to the muons and will measure an average lifetime of 2.2 μs. Observers on the ground know that this clock is running slow. This means that the lifetime of the muons (as measured by clocks on the ground) is longer by an amount determined by the adjustment factor:

$$\tau_{moving} = \gamma \tau_{at\ rest} = (7.09)(2.2\ \mu s) = 15.6\ \mu s$$

Therefore, the average lifetime of the fast-moving muons is 15.6 μs. Note that the shortest time is determined by the clocks *at rest* relative to the muons.

Everyday Physics | *The Twin Paradox*

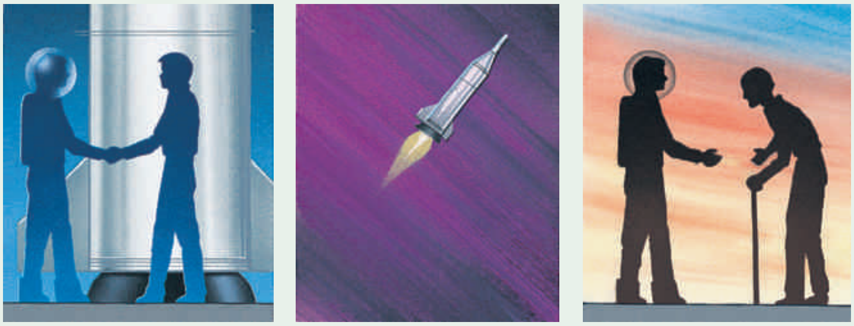
The prediction of time dilation is usually greeted with disbelief. Surely people in different inertial systems can stop their experiment, come together, and compare clocks. They should be able to resolve the question of which clock is really running slower. This feeling was ingeniously expressed in a hypothetical situation that led to an apparent paradox, called the *twin paradox*. One twin gets in a spaceship and flies away from Earth. The spaceship travels out to a distant star and returns to Earth.

The twin on Earth observes that clocks in the spaceship run slower than on Earth. Therefore, the twin in the spaceship ages more slowly. The twin should return from the journey at a younger age than the one who stayed at home. Meanwhile, the twin in the spaceship observes that the clocks on Earth are running slower. So the Earthbound twin will age slower and should be the younger at the reunion. Thus, we have a paradox. How can each twin be younger than the other?

The paradox arises because we assumed that everything was symmetric, that there was no way of deciding who was taking the trip. But the situation is not symmetric. It becomes clear that the twin in the spaceship is taking the trip as soon as the spaceship accelerates to leave or turns around to return. The inertial forces that arise during the acceleration give it away.

It is sometimes thought that the special theory of relativity can be applied only to situations involving inertial systems—that is, where there is no acceleration. This is not true; there are several ways of getting the correct answer within the framework of special relativity. All solutions agree that the twin in the spaceship is younger at the reunion than the twin who stayed on Earth.

Imagine making such a trip. Suppose the journey takes 40 years as measured by clocks on Earth, but only 10 years elapse on the spaceship's clocks. On your return you would find that society's technology and institutions have jumped ahead by 40 years. It is possible that you would return and be younger than your children. The social consequences of this *family* shock could be even more mind boggling than the expected *future* shock that you would experience.



One twin makes a journey to a distant star while the other remains at home. At their reunion, the twin who made the journey is younger than the twin who stayed at home.

Length Contraction

The existence of time dilation suggests that space travel to distant galaxies is possible. Although the galaxies are enormous distances from Earth, space explorers traveling fast enough could complete the trips within their (time-dilated) lifetimes.

An examination of such a trip leads us to another startling consequence of Einstein's ideas. Consider a trip to our nearest neighbor star, Proxima Centauri, which is 42 trillion kilometers from Earth. Even light traveling at its incredible speed takes 4.4 years to make the trip. A spaceship capable of traveling at 99% of the speed of light would make the trip in about 4.5 years, according to clocks on Earth. However, according to Table 10-1, clocks inside the spaceship will record that the trip takes one-seventh as long, or about 0.64 year.

But there is a catch. Both the space travelers and their Earthbound friends agree that their relative velocity is 99% of the speed of light. How, then, can the space travelers reconcile making this trip in only 0.64 year? The distance to

Figure 10-10 According to the observer on the ground, the paint can at the front of the pole explodes before the can at the back. Therefore, the two paint splashes on the ground are closer together.

Proxima Centauri must be *contracted.* The amount of contraction is just right to compensate for the time dilation. Our space travelers measure a distance that is one-seventh as long. Measurements of space, like those of time, change with relative motion.

To see why this happens, we follow Einstein's advice and carefully consider how we measure the length of something. If you are at rest relative to a stick, there is no problem measuring its length. You simply measure it with a ruler, or mark the position of the two ends on the floor and measure the distance between the marks.

What if the stick is moving? Again, you could mark the floor at each end of the stick as it passes by. But you have to be careful. Clearly, you could get a variety of lengths if you mark one end first and the other end at various times later. To obtain the correct length, you must mark the position of the two ends *simultaneously*—for example, by exploding paint cans at each end.

What will a person at rest relative to the stick (Figure 10-10) think of this measurement? She agrees with your procedure but says that the paint cans didn't explode simultaneously. She claims that the paint can at the front exploded earlier. By the time the can at the back exploded, the back end of the stick had moved closer to the first mark. Thus, the length you measured is shorter than hers; that is, the length of a moving stick is contracted.

moving sticks are shorter ▶

Consider another way to measure the length of the moving stick. You could measure the stick's velocity and record the elapsed time between the passing of the front and back ends. Again, the observer on the moving stick disagrees with your results. She says that your clocks are running slower, and the elapsed time is therefore shorter. Once again, your measurement yields a contracted length.

The moving length is equal to the length measured at rest *divided* by the relativistic adjustment factor. This length contraction occurs only along the direction of the relative motion. Lengths along the direction perpendicular to this motion are the same in the two inertial systems.

Q: Assume that both you and your friends in the van are carrying meter sticks pointing along the direction of relative motion. If your friends measure your stick to be $\frac{1}{2}$ meter long, what length would you measure for your friends' stick?

A: The first postulate requires that the situations be symmetric. *Each* observer says that the other's stick is contracted. Therefore, you would also measure your friends' stick to be $\frac{1}{2}$ meter long.

WORKING IT OUT — *Relativistic Lengths*

Let's assume that a train is traveling along a straight, horizontal track at a constant speed of 80% of the speed of light. What is the size of the adjustment factor?

$$\gamma = \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}} = \frac{1}{\sqrt{1-\left(\frac{0.8c}{c}\right)^2}} = \frac{1}{\sqrt{1-0.64}} = \frac{5}{3}$$

Mary is a passenger on the train and measures the length of the dining car to be 30 m. Bill is standing on the platform of a railway station. What will Bill obtain for the length of the dining car?

We know that we should either divide or multiply by the adjustment factor, but which do we do? We know that the length measured in a reference system at rest relative to the object (in this case the dining car) must always be the longest. Therefore, Mary's length will be the longer, and we must divide by the adjustment factor to obtain Bill's length:

$$L_{Bill} = \frac{L_{Mary}}{\gamma} = \frac{30\text{ m}}{\frac{5}{3}} = 18\text{ m}$$

If Mary measures the length of the railway platform to be 120 m, how long will Bill measure it to be?

Bill is at rest relative to the platform and must therefore obtain a longer length. In this case we must multiply by the adjustment factor:

$$L_{Bill} = \gamma L_{Mary} = \frac{5}{3}(120\text{ m}) = 200\text{ m}$$

Spacetime

Einstein's ideas changed the role that time plays in our world view. In the Newtonian world view, we considered motion by looking at the spatial dimensions and looking *independently* at time. Einstein demonstrated that time is not a separate quantity but rather is intimately connected to the spatial dimensions. When space changes, there is a corresponding change in the time. Time is now truly the fourth dimension of **spacetime**.

The theory of special relativity must be self-consistent. All observers must find that events obey the laws of physics. As we have seen, they do not have to agree on their particular measurements, but they must be able to make sense of the events within their own reference system.

A hypothetical situation illustrates this point. Suppose an ingenious student claims that she can fit a 10-meter pole into a 6-meter-long barn (Figure 10-11). Knowing about length contraction, she proposes to propel the pole into the barn at 80% of the speed of light because the adjustment factor is $\frac{5}{3}$, giving a

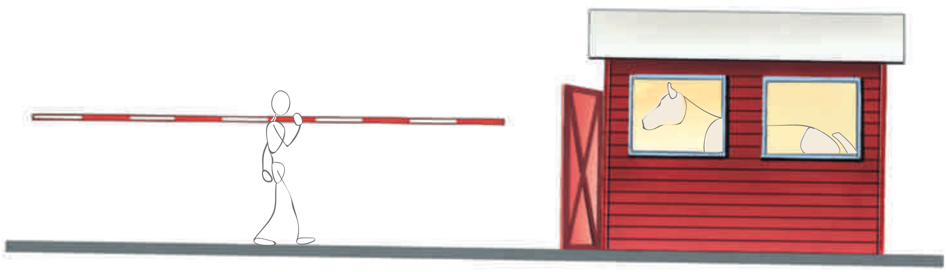


Figure 10-11 The observer on the ground tries to put a 10-meter-long pole in a 6-meter-long barn.

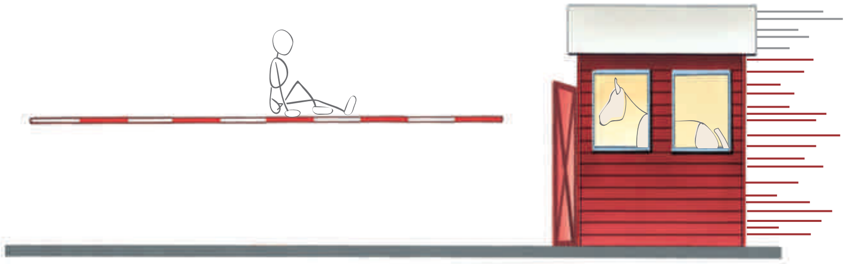


Figure 10-12 The observer on the pole tries to put a 10-meter-long pole in a 3.6-meter-long barn.

moving length of 6 meters. Just enough to fit into the barn! Of course, the pole will only be in the barn for an instant because it is moving very fast. Our ingenious experimenter plans to prove that the pole was entirely in the barn by closing the front door and simultaneously opening the back door.

Now consider this situation from the point of view of a person riding on the pole (Figure 10-12). The pole is 10 meters long, but the barn is moving and is contracted to 3.6 meters! Clearly, he is not going to agree that the pole was ever entirely in the barn, not even for an instant.

There is no paradox, however. The rider does not agree that the back door was opened at the same time that the front door was closed. Recalling that trailing clocks lead, he says that the back door opened before the front door closed. In fact, careful calculations of this situation verify the consistency. The time interval between these events is just enough to allow the "extra" 6.4 meters to pass through.

Relativistic Laws of Motion

The speed of light is the speed limit of the universe.

As we did in our study of the classical ideas of motion, we now expand our considerations beyond describing motion to consider the laws of motion. Many approaches can be taken to develop laws of motion that are consistent with the ideas of special relativity, although we don't have an entirely free hand. The new laws must have a structure that is logical and internally consistent, and the predictions of the laws must agree with the results of experiments. Furthermore, the new formulations must reduce to the older ones (Newton's laws) when the velocities are small because we know Newton's laws work for small velocities.

The form of Newton's second law regarding momentum carries over into special relativity, providing that the expression for the momentum is modified so that $p = \gamma mv$. This is the classical formula multiplied by the adjustment factor. Notice that this expression reduces to the classical one for small speeds because the adjustment factor is very close to 1 in this case. With this modification, the second law is written as

relativistic form of Newton's second law ▶

$$F = \frac{\Delta p}{\Delta t} = \frac{\Delta(\gamma mv)}{\Delta t}$$

Careful analysis of symmetric collisions of identical balls in different inertial reference systems demonstrates that conservation of momentum is still valid provided this relativistic form for momentum is used.

A force acting for a time still produces the same impulse and therefore the same change in the relativistic momentum. However, because the adjustment factor increases with speed, the acceleration decreases and goes to zero as the object approaches the speed of light. This means that a material object cannot be accelerated to a speed equal to or greater than that of light. Nothing can go faster than the speed of light.

Einstein | *Person of the Century*

Albert Einstein (1879–1955) was a great physicist who devoted his life to peace and humanity. Born in Ulm, Germany, he received his basic education in Munich, studied in Italy and Switzerland, and accepted major scientific posts in Berlin just before World War I. After the National Socialists and Hitler took control of Germany, Einstein found refuge and citizenship in the United States.

In his autobiography, Einstein states that at age 3 he was much taken by the fact that an uncle's compass always pointed north—even in a dark closet. Invisible laws of nature seemed to him to be the route to the most powerful understanding of our being and the universe.

His heroes were Newton and Maxwell. Their portraits were always displayed in his office. He received a solid, if for him dull, German education. After a year of individual tutoring, he entered the Swiss Federal Technical University and began serious study of physics. He lived during a period of great upheaval in science and felt revolutionary change in the air.

He began to publish early and in 1905 brought out four important papers. Two founded the study of special relativity. Another on the photoelectric effect explained a puzzling phenomenon and earned him the Nobel Prize in 1921. In 1907 he published his now famous equation on energy and mass: $E = mc^2$. His great work on general relativity, the nature of gravitation, appeared in 1915 in the midst of the greatest war in human history. This powerful theory related gravity to a warping of spacetime.

After the war he worked on early quantum theory but could accept it only as a stopgap until a better theory evolved. He was unpopular in Germany because he was so outspoken against the war, because he was a Jew, and because his theories were so revolutionary and unsettling.

He chose to settle in the United States because he believed it to be an open, democratic society. A research institute was arranged for him at Princeton University. In America he could work more effectively for a homeland for the oppressed Jews. Ironically, this outspoken pacifist triggered American interest in nuclear power. In 1939 he received word from Niels Bohr (see "Bohr: Creating the Atomic World" in Chapter 23) that German scientists had fissioned uranium. He wrote to President Franklin Roosevelt, alerting him officially that atomic power for military use might be possible. He was never active in nuclear research himself and sought mightily to mitigate conditions in which such terrible weapons might be used.


Albert Einstein

He also played a significant role in creating the modern state of Israel and was offered the first presidency of that nation (he declined). He also worked for better Jewish–Arab relations. Einstein was, for most of his life, the most famous scientist in the world and was named "Person of the Century" by *Time* magazine. UNESCO designated 2005 the World Year of Physics, and many physical societies around the world honored the 100th anniversary of Einstein's remarkable year, coincidentally, the 50th anniversary of his death.

A fine writer, Einstein is often the best source to read for those seeking an understanding of his life and work.

—Pierce C. Mullen, historian and author

Sources: Abraham Pais, *Subtle Is the Lord: The Science and Life of Albert Einstein* (Oxford, England: Oxford University Press, 1982); P. A. Schilpp, *Albert Einstein: Philosopher-Scientist* (New York: Harper, 1949).

The law of conservation of energy is also valid in special relativity. If we calculate the work done by a force acting on an object that is initially at rest and equate this work to the kinetic energy of the object as we did in classical physics, we arrive at the expression

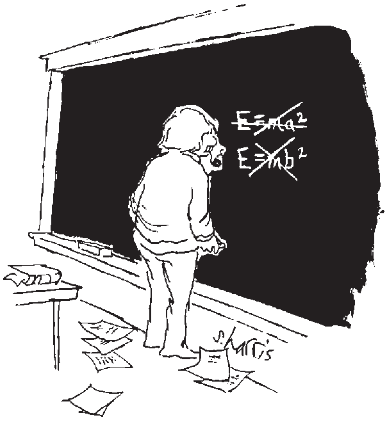
$$KE = \gamma mc^2 - mc^2$$

◀ **relativistic kinetic energy**

The relativistic kinetic energy of an object is equal to the difference between two terms. The second term, mc^2, is the energy of the particle at rest. Therefore, it is known as the **rest-mass energy** E_o. This is the origin of Einstein's famous mass–energy equation

$$E_o = mc^2$$

◀ **mass–energy relationship**



Because the kinetic energy is the additional energy of the object due to its motion, the first term, γmc^2, is identified as the total energy of the particle. This expression tells us that the total energy of an object increases with speed. In fact, because the adjustment factor approaches infinity as the speed approaches that of light, the energy also approaches infinity.

Notice also that even when the object is at rest, it has an amount of energy mc^2 stored in its mass. Mass is another form of energy. Thus, the law of conservation of energy must be modified once more to include a new form of energy, mass-energy. This relationship produced a major change in the physics world view. It tells us that mass can be converted into energy and energy can be converted into mass. We will discuss this more fully when we discuss nuclear reactors and the properties of subatomic particles.

The authors of some popular books and articles about special relativity state that mass increases with speed. These authors define a relativistic mass $m = \gamma m_o$, where m_o is called the *rest mass* and is the mass measured in a system at rest relative to the object. This statement does not change any of the mathematics, but it does change the interpretation of some of the expressions. The modern view is that mass is an invariant and that the introduction of a relativistic mass is unnecessary and sometimes leads to misconceptions.

What is the acceleration of a ball dropped in an accelerating spaceship?

General Relativity

For about a decade after Einstein's publication of his theory of special relativity, he worked on generalizing his ideas. The outcome—his **general theory of relativity**—deals with the roles of acceleration and gravity in our attempts to find our place in the universe.

Armed with his deep relativistic philosophy, Einstein started by expanding the principle of relativity to include all areas of physics and noninertial, or accelerating, reference systems. Imagine a spaceship very far from any stars that is accelerating at 10 (meters per second) per second. The astronauts feel an inertial force equivalent to the gravitational force they would feel on Earth. If they release a ball, it falls freely with an acceleration of 10 (meters per second) per second. However, an observer in an inertial system outside the spaceship would give a different explanation: The ball continues in the forward direction with the velocity it had at the time of release. The floor accelerates toward the ball at 10 (meters per second) per second, making it seem as if the ball were falling.

The fact that the astronauts can attribute their motion to gravitational effects is possible only because the mass that appears in Newton's second law (Chapter 3) is identical to the mass that appears in the universal law of gravitation (Chapter 5). It might seem surprising that these two notions of mass are not automatically the same, but recall that they arise in different physical circumstances. Newton's second law gives a relationship between applied force and the resulting acceleration. This idea of mass depends on the inertial properties of mass and is therefore called the **inertial mass**. The universal law

Q: What would the astronauts observe if they released two balls with different masses?

A: The two balls would appear to fall with the same acceleration. This is easiest to see from outside the spaceship. The two balls move side by side with the same velocity while the floor accelerates toward them.

of gravitation refers to the strength of the attractive force between two objects. This mass is known as the **gravitational mass**. Experiments have shown that inertial and gravitational masses differ by less than a part per billion.

◀ gravitational mass = inertial mass

As a result of the equality of inertial and gravitational mass, any experiment using material objects would not be able to reveal to the astronauts whether the force is due to the gravitational attraction of a nearby mass or the accelerated motion of their spaceship. Believing that *all* motion is relative, Einstein felt that the astronauts could not make any distinction between the two alternatives. He formalized his belief as the **equivalence principle**:

Constant acceleration is completely equivalent to a uniform gravitational field.

◀ equivalence principle

Before Einstein there seemed to be a way for the astronauts to distinguish between gravitational and inertial forces. According to the ideas of that time, the astronauts would only have to shine a flashlight across their windowless ship and observe the path of the light by placing frosted glass at equal intervals across the spaceship, as shown in Figure 10-13. With the ship at rest on a planet, the beam of light would pass straight across the room because the gravitational field would have no effect on it. However, in an accelerating spaceship, the astronauts could see the light bend. While the light travels across the ship, the ship accelerates upward, making the differences in the vertical positions on adjacent screens get larger and larger.

Einstein agreed that light would bend in the accelerating spaceship but disagreed that light would be unaffected in the ship in the presence of gravity. Because he firmly believed in the equivalence principle, he felt that the astronauts should not be able to tell any difference between the two situations. Einstein was forced to conclude that light is bent by gravity. All experimental measurements are in agreement with this prediction.

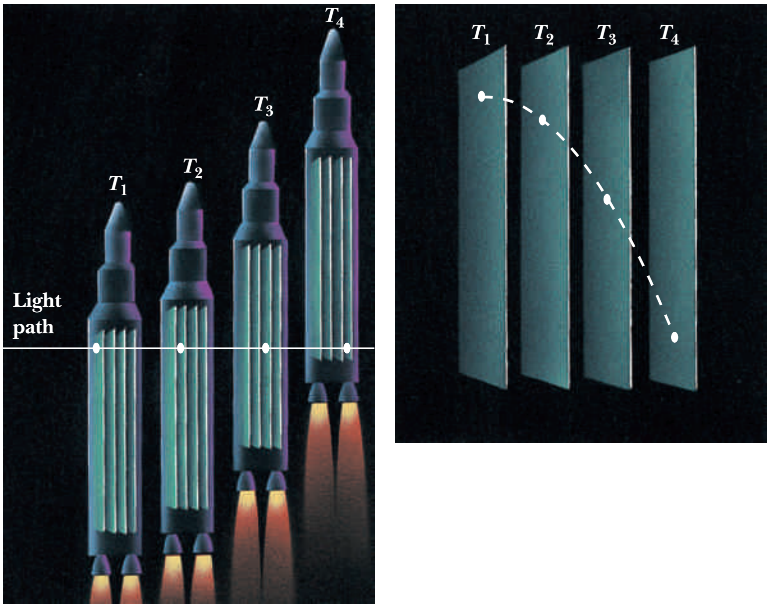


Figure 10-13 While the light travels across the spaceship, the spaceship accelerates upward, causing the light to intersect the frosted glass closer and closer to the floor. The path relative to the ship is a parabola just like that of a falling ball that is projected horizontally on Earth.

FLAWED REASONING

A space shuttle is in orbit around Earth. One of the astronauts turns on the headlights. He has studied the theory of general relativity and knows that the beam of light will experience the same acceleration as the space shuttle. He quickly glances in the rearview mirror expecting to see the light from his own headlights, which he thinks should orbit Earth just like the space shuttle. **What is wrong with his reasoning?**

ANSWER The space shuttle and everything in it are falling around Earth in a circular orbit. The space shuttle is moving fast enough that by the time it has fallen 5 meters, it is still the same distance from Earth's surface. The light from the headlights is traveling much faster than the space shuttle, so the light will leave Earth orbit before it drops 5 meters.

Everyday Physics | *The Global Positioning System (GPS)*

If you ever get seriously hurt while hiking in the mountains, two products of modern technology may save your life: you can use a cell phone to call for help, and you can use a GPS receiver to tell the rescuers where to find you.

Beginning in 1969, the U.S. military developed the Global Positioning System to accurately determine locations any place on or near Earth's surface. This is accomplished with 24 satellites arranged in groups of four in each of six orbital planes. A worldwide network of ground stations monitors the satellites and uploads time and orbital data. Each satellite sends out digitally coded information that gives the time the information was sent and the location of the satellite at that time.

GPS receivers are being installed in automobiles to aid travelers in finding their way.

Assume for the moment that the clock in your GPS receiver is synchronized with the clocks in the GPS satellite. Knowing the speed of light in the atmosphere and the time delay in receiving the time code tells you how far the receiver is located from the satellite. This determines the location of your receiver to be some place on the surface of a sphere centered on the location of the satellite at the time the signal was sent. The reception of a signal from a second satellite narrows the location of your receiver to be along the intersection of two spheres, one centered on each satellite. The signal from a third satellite narrows the location to a single point determined by the intersection of three spheres. In practice the GPS receiver must receive signals from a minimum of four satellites, the fourth being used to determine the difference in times on the clock (usually a crystal clock) in the receiver and GPS time. GPS provides an accuracy of 15 meters in the horizontal plane and 22 meters in the vertical plane.

Large improvements in accuracy can be obtained by using differential GPS. The locations of stationary receivers are accurately surveyed to determine their locations. Comparison of these locations with locations determined by GPS yields the errors in these positions. A map of the errors can then be broadcast to portable receivers to correct their readings. This results in an accuracy of 3–5 meters. The Wide Area Augmentation System (WAAS) developed for aviation and marine navigation uses a similar technique to obtain an accuracy of less than 3 meters. More sophisticated techniques used in surveying can yield measurements with an accuracy of centimeters.

It is crucial to the operation of the GPS that all satellites use the same time to a high degree of accuracy. This requires that the effects of both special and general relativity be taken into account. Don't let anyone tell you that relativity doesn't have any consequences in the real world.

1. In what way does the theory of relativity affect the accuracy of the GPS?
2. Your neighbor claims that relativity is just a crazy idea. What evidence could you use to convince him that it is a respectable theory?

Warped Spacetime

Einstein's work in general relativity also showed that time is altered by a gravitational field. Clocks run slower in a gravitational field. The stronger the gravitational field, the slower the clocks run.

The special theory of relativity has shown us that there is an intimate relationship between space and time. Because gravity affects time, we should also expect it to affect space.

The Newtonian world view considered space to be flat (Euclidean) and completely independent of matter. Objects naturally travel in straight lines in this space. The addition of matter introduced forces that caused objects to deviate from these natural paths. The matter interacted with the objects but did not affect space. Time was independent of space.

The Einsteinian world view begins with a four-dimensional flat spacetime. The addition of matter warps this spacetime. The matter does not act directly on objects but changes the geometry of space. The objects travel in "straight" lines in this four-dimensional spacetime. Although these lines are straight in four dimensions, the paths that we view in three-dimensional space are not necessarily straight. This situation is analogous to that in which the shadow of a straight stick is projected onto the surface of a sphere. The shadow is not necessarily straight, as shown in Figure 10-14.

Figure 10-14 The shadow of a straight stick projected onto a sphere is not necessarily straight.

We can see what is meant by replacing the gravitational field by a warped spacetime by considering the following situation. Imagine that you are looking down into a completely darkened room where somebody is rolling bowling balls that glow in the dark along the floor. You record the paths of the balls, and your record looks like Figure 10-15.

What reasons can you give to explain the pattern that emerges from these paths? You may suggest that the balls are attracted to an invisible mass that is fixed in the center of the floor [Figure 10-16(a)]. Or you may suggest that the floor has a dip in the center [Figure 10-16(b)].

In his classic book *Flatland,* author and mathematician Edwin Abbott tells a bizarre tale of an inhabitant of a two-dimensional world. This fellow was given

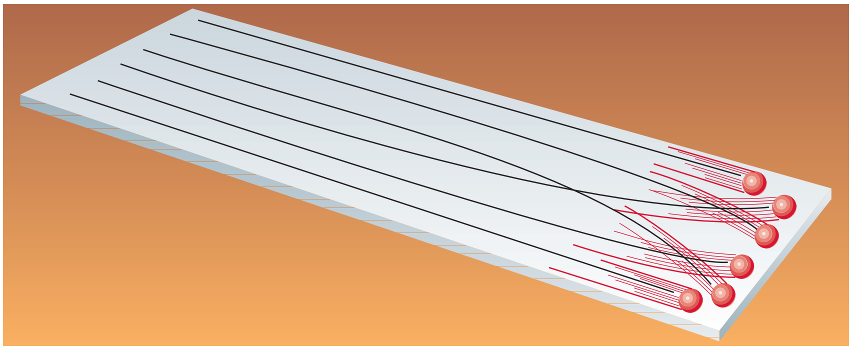


Figure 10-15 The paths of the glowing bowling balls as seen in the dark.

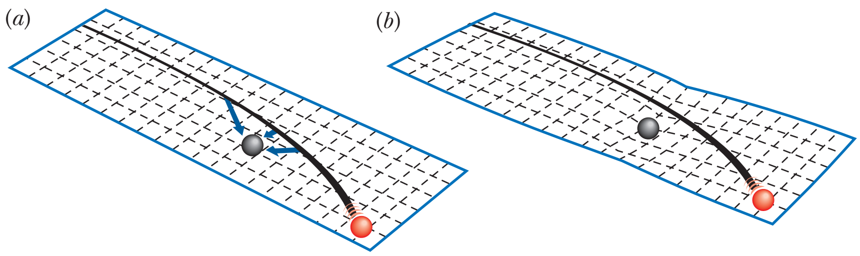


Figure 10-16 Two possible explanations for the paths in Figure 10-15. (a) The bowling balls are attracted by a mass. (b) The mass causes the floor to sag.

Everyday Physics | *Black Holes*

A bizarre astronomical object has dramatically confirmed the ideas that Einstein put forth in his theory of general relativity. Stars are known to collapse because of their own gravitational attraction after their source of fuel is exhausted. Stars more massive than our Sun can collapse to objects so compact that they are only tens of kilometers in diameter. One type of such object is so massive and so small that the increased gravity near the star would prohibit anything—including light—from escaping. This is called a *black hole* because no light can come from this region of space.

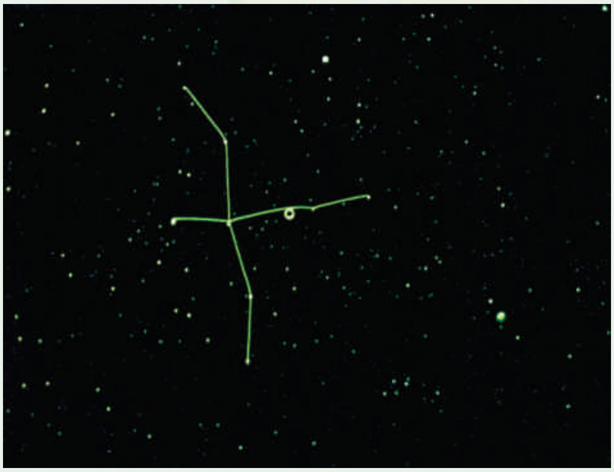
Because even light can't escape from a black hole, we have to search for more indirect ways of "seeing" a black hole. The key to finding a black hole is the influence its gravitational field has on nearby objects. Most stars in the universe occur in groups of two or more that are bound together by their mutual gravitational attraction. In some binary star systems, one of the stars is compact and not visible. The mass of the unseen star can be determined by examining the behavior of the visible companion. The visible star orbits along an elliptical path because the compact star continuously exerts a centripetal force on the visible star.

Current, well-established theories of stellar evolution indicate that of several possibilities for the end stages of stars, only black holes can have masses larger than five times the mass of the Sun. Although the determination of the masses of the unseen stars in binary stars is not very accurate, several cases are known with masses large enough to be black holes.

Current evidence indicates that Cygnus X-1, the first X-ray source observed in the constellation Cygnus, is very compact and has a mass at least 9 times that of the Sun. (The best experimental value is 16 solar masses.) It is almost certainly a black hole. Several other binary star systems also contain good candidates for black holes.

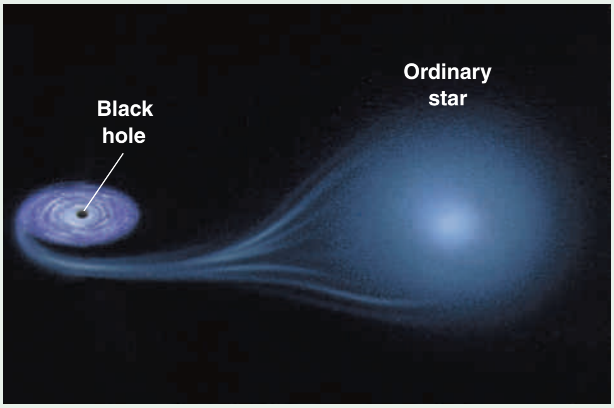
Although light from a black hole cannot escape, light from events taking place near the black hole should be visible. In binary systems, a black hole's powerful gravitational field may capture mass from its companion star. As the mass falls into the black hole, it should emit X rays. Although this is not a black hole "fingerprint," X rays compatible with the existence of black holes have been observed.

The strongest evidence for the existence of black holes is the presence of supermassive, compact objects at the centers of galaxies. Observations of the orbits of stars near the centers of galaxies indicate that the stars are orbiting very massive yet very small objects. Our own Milky Way Galaxy has a black hole at its center with a mass about 2.5 million times as large as the mass of the Sun. Most galaxies that have been examined closely have a black hole at their center, some with masses greater than a billion solar masses.



Gerald F. Wheeler

The circle indicates the location of Cygnus X-1, which is believed to be a black hole.



Matter from an ordinary star falling into its companion black hole produces characteristic X rays.

Some galaxies are expected to have two large black holes at their centers. These binary black holes orbit each other because of their mutual gravitational attraction and may exist because of the collision and coalescing of galaxies. The detection of gravitational waves (see Chapter 28) emitted by these binary black holes would enhance our understanding of black holes.

1. What evidence suggests that black holes exist?
2. How do we know that the black hole at the center of our galaxy has a mass 2.5 million times the mass of the Sun?

the "pleasure" of going to another dimension. Once he went into the third dimension, the shape of his normally flat world became obvious to him. Things that were incomprehensible in Flatland—such as looking inside a closed figure—became trivial in the third dimension. When he returned to Flatland, he tried to convince his fellow inhabitants of his newly gained insight. They thought he was insane with his strange talk of "up."

Are we similarly doomed to never understand four-dimensional spacetime? If our space has certain shapes that are obvious in the next dimension, can we deduce them without stepping into that additional dimension? Much as two-dimensional creatures on the surface of a sphere can examine their geometry to determine that their space is not flat, we can examine the geometry of our space to learn about the geometry of spacetime.

Summary

The ideas contained in the special theory of relativity are based on two postulates: (1) the laws of physics are the same in all inertial reference systems, and (2) the speed of light in a vacuum is a constant, regardless of the speed of the source or the observer.

As a consequence of adopting these two postulates, observers in different inertial reference systems cannot agree on the simultaneity of events at different places or on the synchronization of separated clocks. These observers do agree that trailing clocks lead.

Time seems normal in one's own reference system but is dilated when viewed from another reference system. Both observers see the other's clocks running slower. The time interval in the moving system is equal to the interval in the rest system multiplied by the relativistic adjustment factor

$$\gamma = \frac{1}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$

Observers in two different inertial systems agree that objects in the other's system are shorter along the direction of the relative velocity. However, both observers agree on the relative speed of the two systems.

The conservation laws are valid in special relativity if we introduce the ideas of relativistic momentum and energy and consider mass to be another form of energy. The speed of light is the speed limit of the universe.

In general relativity, gravitational fields can replace accelerations. The equivalence principle requires that the mass that appears in Newton's second law (inertial mass) be identical to the mass that appears in the universal law of gravitation (gravitational mass) and that light be bent by gravitational fields.

Space and time form a four-dimensional spacetime that is warped by the presence of matter. Objects travel in straight lines in this four-dimensional spacetime, but the paths that we view in three-dimensional space are not necessarily straight. Time is slowed as the strength of the gravitational field increases.

CHAPTER 10 *Revisited*

Time intervals are measured in comparison to some kind of periodic motion. Even though all observers in our own inertial reference system will agree with our foolproof method for measuring time, observers moving relative to us will not accept these time measurements. There is no absolute time; time measurements depend on the particular observer.

Key Terms

equivalence principle Constant acceleration is completely equivalent to a uniform gravitational field.

ether The hypothesized medium through which light was believed to travel.

first postulate of special relativity The laws of physics are the same for all inertial reference systems.

general theory of relativity An extension of the special theory of relativity to include the concept of gravity.

gravitational mass The property of a particle that determines the strength of its gravitational interaction with other particles. Gravitational mass is measured in kilograms.

inertial mass An object's resistance to a change in its velocity. Inertial mass is measured in kilograms.

rest-mass energy The energy associated with the mass of a particle. Rest-mass energy is given by $E_o = mc^2$, where c is the speed of light.

second postulate of special relativity The speed of light in a vacuum is a constant regardless of the speed of the source or the speed of the observer.

spacetime A combination of time and three-dimensional space that forms a four-dimensional geometry.

special theory of relativity A comprehensive theory of space and time that replaces Newtonian mechanics when velocities get very high.

Questions and exercises are paired so that most odd-numbered are followed by a similar even-numbered.
Blue-numbered questions and exercises are answered in Appendix B.
indicates more challenging questions and exercises.
WebAssign Many Conceptual Questions and Exercises for this chapter may be assigned online at WebAssign.

Conceptual Questions

1. If you were located in a spaceship traveling with a constant velocity somewhere in the Galaxy, could you devise experiments to determine your speed? If so, what kinds of experiments?

2. If you were on the starship *Enterprise* in a room with no windows, could you devise experiments to determine your acceleration? If so, what kinds of experiments?

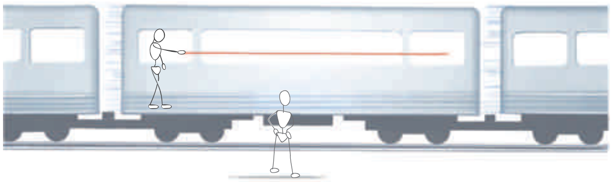
3. Einstein's theory of special relativity is often interpreted as saying, "Everything is relative and there are no absolutes." Is this interpretation consistent with the fundamental postulates of the theory?

4. If Michelson and Morley had detected an ether in their experiment, what implications would it have had for the first postulate of special relativity?

5. Your friend is driving her 1964 Thunderbird convertible straight toward you at 40 miles per hour. She stands up and throws a baseball forward at 30 miles per hour. How fast do you see the ball approaching you?

6. Your friend from Question 5 finds that hanging "fuzzy dice" from the rearview mirror allows the car to travel at up to 98% of the speed of light. She is driving straight toward you when she turns on her headlights. How fast do you see the light approaching you?

7. An observer on the train in the following figure stands in the back of the car. He turns on a light and measures the time it takes for the light to get to the front of the car, bounce off a mirror, and return to him. (Assume that the light is traveling in a vacuum.) Knowing the length of the car, he can calculate the speed of light. Will he obtain a speed less than, greater than, or equal to c? Explain.



Questions 7, 8, 13, 14, and 35–40. A train is traveling along a straight, horizontal track at a constant speed that is only slightly less than that of light.

8. If an observer on the ground uses her own instruments to measure the speed of the light in Question 7, will she obtain a value less than, greater than, or equal to c? Explain.

9. According to the special theory of relativity, a twin who makes a long trip at a high speed can return to Earth at a younger age than the twin who remains at home. Is it possible for one twin to return before the other is born? Explain.

10. Suppose that in the situation depicted in Figure 10-3, the observer on the ground saw the rear paint can explode before the front one. For the observer in the van, is it possible that the two explosions occurred (a) simultaneously, (b) in the order as observed from the ground, or (c) in the reverse order as observed from the ground? Explain.

11. A particularly fortunate astronomer observes light from two supernovae (exploding stars) at exactly the same time. One supernova is in the nearby Andromeda Galaxy while the other is in the more distant Whirlpool Galaxy. Were the two explosions simultaneous?

12. Two lighthouses are located 4 miles apart. An observer in the middle sees flashes from the two lighthouses at exactly the same time and concludes that the flashing events are simultaneous. A second observer, located 1 mile from one lighthouse and 3 miles from the other, does not receive the flashes at the same time. Does this observer disagree with the first one about whether the events were simultaneous? Explain.

13. An observer on the ground reports that as the midpoint of the train in the figure for Question 7 passes her, simultaneous flashes occurred in the engine and caboose. How would an observer on the train describe these same events?

14. An observer on the train in the figure for Question 7 determines that firecrackers go off simultaneously in the engine and in the caboose. How would an observer on the ground describe these same events?

15. As a friend passes you at a very high speed to the right, he explodes a firecracker at each end of his skateboard. These explode simultaneously from his point of view. Which one explodes first from your point of view? How must a third person be moving for her to have observed the other firecracker explode first?

16. Two lights on lampposts flash simultaneously as seen by an observer on the ground. How would you have to be moving in order to see (a) the right-hand light flash first? (b) The left-hand light flash first?

17. It is possible for observers moving relative to one another to disagree on the order of two events. However, the theory of special relativity preserves cause and effect. If one event caused, or could have caused, the other, then the order of the two events must be preserved for all observers. Two light sources, A and B, are located 186,000 miles apart (the distance light travels in 1 second). An observer at the midpoint between the sources receives a light signal from source A $\frac{1}{2}$ second before receiving a signal from source B. Is it possible that the light from source A caused source B to flash? Could another observer have seen B flash before A?

18. If the signal from source B in Question 17 was received 2 seconds after the signal from source A, is it possible that the light from source A caused source B to flash? Could another observer have seen B flash before A?

19. Space travelers on the way to colonize a planet orbiting a distant star decide to cook a "three-minute egg." Would a clock on Earth record the cooking time as less than, equal to, or greater than 3 minutes? Why?

20. Skip Parsec ventured into space without taking his watch. Wishing to cook a perfect "three-minute egg" on board his fast-moving spaceship, Skip is forced to rely on a clock on Earth. Because Skip missed the day that special relativity was taught at training camp, he cooks his egg for 3 minutes according to the Earth clock. Is his egg undercooked or overcooked?

21. If a musician plays middle C on a clarinet while traveling at 85% of the speed of light in a spaceship, will passengers in the ship hear a lower note, a higher note, or the same note? Why?

22. Superman wants to travel back to his native Krypton for a visit, a distance of 3,000,000,000 kilometers. (It takes light 10,000 seconds to travel this distance.) Superman can hold his breath for only 1000 seconds, but he can travel at any speed less than that of light. Can he make it?

23. In an experiment to measure the lifetime of muons moving through the laboratory, scientists obtained an average value of 8 microseconds before a muon decayed into an electron and two neutrinos. If the muons were at rest in the laboratory, would they have a longer, a shorter, or the same average life? Why?

24. On average, an isolated neutron at rest lasts for 17 minutes before it decays. If neutrons are moving relative to you, will you observe that they have a longer, a shorter, or the same average life? Explain.

25. A warning light in the engine of a fast-moving train flashes once each second according to a clock on the train. Will an observer on the ground measure the time between flashes to be greater than, less than, or equal to 1 second? Explain.

26. A warning light on the ground flashes once each second. Will an observer on a fast-moving train measure the time between flashes to be greater than, less than, or equal to 1 second? Why?

27. Peter volunteers to serve on the first mission to visit Alpha Centauri. Even traveling at 80% of the speed of light, the round-trip will take a minimum of 10 years. When Peter returns from the trip, how will his biological age compare with that of his twin brother, Paul, who will remain on Earth?

28. Is it physically possible for a 30-year-old college professor to be the natural parent of a 40-year-old student? Would this imply that the child was conceived before the professor was born?

29. What does the special theory of relativity say about the possibility of the event described in the following limerick?

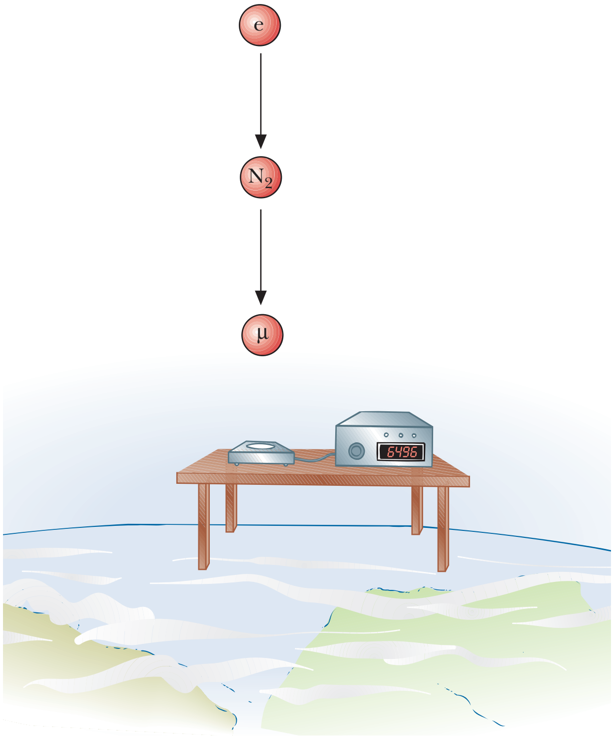
    There was a young lady named Bright
    Who could travel much faster than light.
    She set out one day
    In a relative way
    And returned on the previous night.

30. In *A Connecticut Yankee in King Arthur's Court,* Mark Twain chronicles the adventures of a New England craftsman who in 1879 is suddenly transported back in time to Camelot in the year 528. What does the special theory of relativity say about this possibility? What effect would such a trip have on our beliefs about cause and effect?

31. Suppose you had a row of clocks along a line perpendicular to the direction of relative motion. Would observers in both reference systems agree on the synchronization of these clocks? Explain.

32. Two events occur at different locations along a line perpendicular to the direction of relative motion. Will observers in both reference systems agree on the simultaneity of these events? Explain.

33. Muons are created in the upper atmosphere, thousands of meters above sea level. A muon at rest has an average lifetime of only 2.2 microseconds, which would allow it to travel an average distance of 660 meters before disintegrating. However, most muons created in the upper atmosphere survive to strike Earth. This effect is often explained in terms of time dilation. In this explanation, is the observer in the reference system of Earth or the reference system of the muon? Explain.



34. An alternative explanation for the survival of muons as described in Question 33 invokes length contraction. In this explanation, is the observer in the reference system of Earth or the reference system of the muon? Explain.

35. An observer on the ground and an observer on the train in the figure for Question 7 each measure the distance between two posts located along the tracks. The observer on the ground measures the distance to be 100 meters. Does the observer on the train obtain a measurement that is less than, equal to, or greater than 100 meters? Why?

36. Suppose a ground-based observer in Question 35 measures the distance between the posts at 100 meters. She then places exploding paint cans on the two posts and detonates them simultaneously as the train passes. An observer on the train then measures the distance between the paint splatters on the side of the train. Will his measurement be less than, equal to, or greater than 100 meters? Why?

37. An observer on the ground and an observer on the train in the figure for Question 7 each measure the length of the train. The observer on the train measures the distance to be 400 meters. Does the observer on the ground obtain a measurement that is less than, equal to, or greater than 400 meters? Why?

38. Suppose a train-based observer in Question 37 measures the length of the train to be 400 meters. He then places exploding paint cans on the front and back of the train and detonates them simultaneously. An observer on the ground then measures the distance between the paint splatters left on the tracks. Will her measurement be less than, equal to, or greater than 400 meters? Why?

39. An observer on the ground and an observer on the train in the figure for Question 7 each measure the distance between the rails. Does the observer on the ground obtain a longer, a shorter, or the same distance as the observer on the train? Explain.

40. An observer on the ground and an observer on the train in the figure for Question 7 each measure the width of the train. Does the observer on the ground obtain a longer, a shorter, or the same width as the observer on the train? Explain.

41. An observer on the ground claims that the engine of a rapidly moving train came out of a tunnel at the same time as the caboose entered.
    a. Would an observer on the train agree? If not, which event would the observer say happened first?
    b. According to this observer, which is longer, the train or the tunnel?
    c. Are your answers consistent with each other?

42. An observer on a rapidly moving train claims that the engine came out of the tunnel at the same time as the caboose entered it.
    a. Would an observer on the ground agree? If not, which event would the observer say happened first?

b. According to this observer, which is longer, the train or the tunnel?

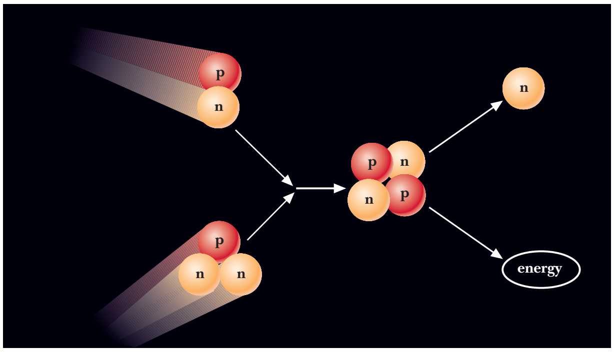
c. Are your answers consistent with each other?

43. A proton is accelerated from 10% to 99% of the speed of light. If the magnitude of the proton's acceleration is to remain constant during this interval, how does the force exerted on the proton have to change as it speeds up?

44. A constant force acts on a proton and causes it to speed up. Does the magnitude of the proton's acceleration increase, decrease, or remain constant as its speed gets closer and closer to the speed of light?

45. Why is it *not* correct to claim that "matter can be neither created nor destroyed"?

46. In a nuclear fusion reaction, one deuterium atom (one proton and one neutron) combines with one tritium atom (one proton and two neutrons) to form one helium atom (two protons and two neutrons) plus a free neutron. In this reaction a huge amount of energy is released. Using Einstein's idea of mass–energy equivalence, what can you conclude about the mass of the final products compared to the mass of the initial fuel?



47. An artist is making a metallic statue of Einstein. Does the mass of the statue change as the metal cools? If so, does it get larger or smaller?

Peter McGahey

48. In view of the fact that clocks run slower and meter sticks are shorter in a moving system, how is it possible for an observer in a moving system to obtain the same speed for light as we do in our system?

49. What types of reference systems does the general theory of relativity address that are specifically excluded from the special theory of relativity?

50. In what way is the special theory of relativity more "special" than the general theory of relativity?

51. The postulates of the special theory of relativity imply that no experiment can distinguish between two reference systems moving at different constant velocities. Does the statement of the general theory of relativity imply that no experiment can distinguish between two reference systems moving with different constant accelerations?

52. Student 1 claims, "General relativity says that there is no experiment I can do in a closed room to tell whether my system is accelerating or not accelerating, which means that the path of a thrown ball should be the same in both systems." Student 2 counters, "The path of the ball could be different. General relativity only says that you can't tell whether it's different because the system is accelerating or because of the presence of some new gravitational force." Which student do you agree with?

53. Jordan and Blake are asked to compare the masses of two objects. Jordan holds one object in each hand and shakes them. Blake holds the objects stationary in each hand. Which student is comparing the gravitational masses of the objects, and which is comparing the inertial masses? Explain your reasoning.

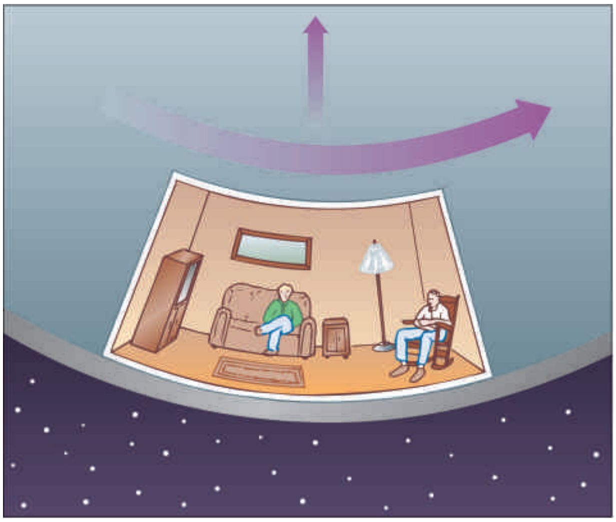
54. You are an astronaut in deep space and you are holding a sledgehammer in one hand and a nail in the other. How could you determine which object has the greater mass? Would you be comparing the gravitational masses or the inertial masses?

55. Imagine a universe in which inertial and gravitational masses are not the same. Specifically, if you double the inertial mass, the gravitational mass increases three times. If you were to drop a hammer and a penny from the same height above the floor, which would hit first? Explain your reasoning.

56. Imagine a universe in which inertial and gravitational masses are not the same. Specifically, if you double the gravitational mass, the inertial mass increases three times. If you were to drop a hammer and a penny from the same height above the floor, which would hit first? Explain your reasoning.

57. Spaceship A is traveling through deep space with twice the acceleration of spaceship B. If the passengers on the two spaceships believe that they are actually sitting on planets with identical masses, which passengers believe their planet has the smaller radius? Why?

58. To create "artificial gravity" for inhabitants of a space station located in deep space, the station is rotated, as shown in the following figure. If one of the inhabitants were to compare the weight of a ball held near the floor to its weight near the ceiling, which would be greater, and why? Compare this to the case in which a ball's weight is measured as it is moved up from Earth's surface.



59. Why do we usually not notice the bending of light?

60. The barrel of a rifle and a laser are both pointed directly toward a target that is 1000 meters away. General relativity says that the bullet and the beam of light from the laser experience the same acceleration, and yet the bullet hits the target well below the beam of light. How can you explain this result?

61. You are asked to predict whether a clock at the North Pole would run faster or slower than one at the equator. You know that because Earth is somewhat flattened at the poles, the clock at the North Pole would be closer to Earth's center. You also know that Earth is spinning, so the clock at the equator has a centripetal acceleration. Will the clock at the North Pole tend to run faster or slower than the one at the equator because of (a) Earth's shape and (b) Earth's spin?

62. We normally describe Earth as orbiting the Sun as a result of the Sun's gravitational attraction of Earth. What alternative explanation does general relativity provide to explain this orbital motion?

Exercises

63. The Moon shines by reflecting light from the Sun. The distance from Earth to the Moon is 3.84×10^8 m, and the distance from Earth to the Sun is 1.5×10^{11} m.
   a. How long does it take for light to reach Earth from the Sun?
   b. How long does it take for light to reach Earth from the Moon?

64. If it takes light 4.4 years to reach Earth from the nearest star system, how far is it to the star system?

65. When Venus is closest to Earth, it is approximately 45 million km away. If the radio telescope at Arecibo, Puerto Rico, bounces a radio signal from Venus's surface, how long will it take the radio signal to make the round-trip?

Dr. Seth Shostak/Science Photo Library/ Photo Researchers, Inc.

66. How long would it take a radio signal to reach a space probe in orbit about Saturn when Saturn is 1.5×10^{12} m from Earth?

67. What is the size of the adjustment factor for a speed of $0.4c$?

68. What is the size of the adjustment factor for a speed of 25% that of light?

69. A pi meson (called a pion) is one of the elementary particles discussed in Chapter 27. The average lifetime of a pion moving at 99% the speed of light is measured to be 2.69 nanoseconds (1 ns = 10^{-9} s). What would be the average lifetime of a pion at rest in the laboratory?

70. The average lifetime of isolated neutrons measured at rest relative to the lab is 920 s. What is the average lifetime of neutrons traveling at 80% of the speed of light?

71. An astronaut traveling at 99% of the speed of light waits 4 h (on his watch) after breakfast before eating lunch. To an observer on Earth, how long did the astronaut wait between meals?

72. The ground-based mission doctor for the astronaut in Exercise 71 is concerned that the astronaut is getting out of shape and requires him to exercise. The doctor tells the astronaut to begin pedaling the stationary bicycle and

continue until she tells him to stop. She waits for 1 h on her clock. How long does the astronaut have to exercise according to his watch?

73. A ground-based observer measures a rocket ship to have a length of 60 m. If the rocket was traveling at 50% of the speed of light when the measurement was made, what length would the rocket have if brought to rest?

74. A rocket ship is 80 m long when measured at rest. What is its length as measured by an observer who sees the rocket ship moving past at 99% of the speed of light?

75. The conductor of a high-speed train uses a meter stick to measure the length of her train at 200 m while the train is stopped at the station. The train then travels at 80% of the speed of light (this is a super-supersonic train!). If she repeats the measurement on the moving train, what answer will she get?

76. An observer standing beside the tracks in Exercise 75 measures the length of the moving train as it goes by. What value does he get?

77. What is the distance to the nearest star system measured by an observer in a rocket ship traveling to the star system with a speed of $0.95c$? (The distance is 42 trillion km as measured by an observer on Earth.)

78. The pilot of an interstellar spaceship traveling at $0.98c$ determines the diameter of our Milky Way Galaxy to be about 1.2×10^{14} km. What value would an Earth-based observer calculate for the Galaxy's diameter?

79. According to the classical form of Newton's second law, $F\Delta t = \Delta p$, it would require a force of 9.5 N acting for a year to accelerate a 1-kg mass to a speed of $0.9999c$. Using the relativistic form of Newton's second law, what force is required?

80. Calculate the impulse ($F\Delta t$) needed to accelerate a 1-kg mass to 80% of the speed of light, using both the classical and relativist forms of Newton's second law of motion.

81. How fast would a proton have to be traveling for its kinetic energy to equal its rest-mass energy?

82. By what factor does the total energy of a particle increase when its speed doubles from $0.4c$ to $0.8c$?

83. A spaceship in deep space has a velocity of 200 km/s and an acceleration in the forward direction of 5 m/s^2. What is the acceleration of a ball relative to the spaceship after it is released in this spaceship?

84. Two spaceships, one red and one blue, are traveling through deep space. The red spaceship has a velocity of 20 m/s and an acceleration of 40 m/s^2, and the blue spaceship has a velocity of 40 m/s and an acceleration of 20 m/s^2. In which spaceship do the astronauts experience the greater effective gravitational force?

85. A spacecraft is descending to land on planet Y and slows by 4 m/s every second. The strength of the planet's gravitational field is 7 N/kg. If the passengers in the spacecraft account for the forces they feel in terms of a single gravitational field, how strong would this field have to be?

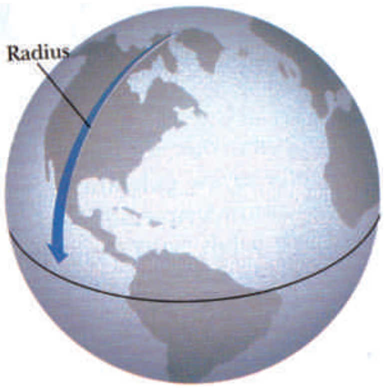
86. A windowless spaceship is lifting off the surface of planet X with an acceleration of 20 m/s^2. The strength of the planet's gravitational field is 10 N/kg. If the passengers in the spacecraft account for the forces they feel in terms of a single gravitational field, how strong would this field have to be?

87. If light could somehow continuously travel perpendicular to a gravitational field with a strength of 10 N/kg—the strength at Earth's surface—how far would the light bend in 1 s?

88. How far would light bend because of gravity in traveling across the United States, a distance of approximately 5000 km?

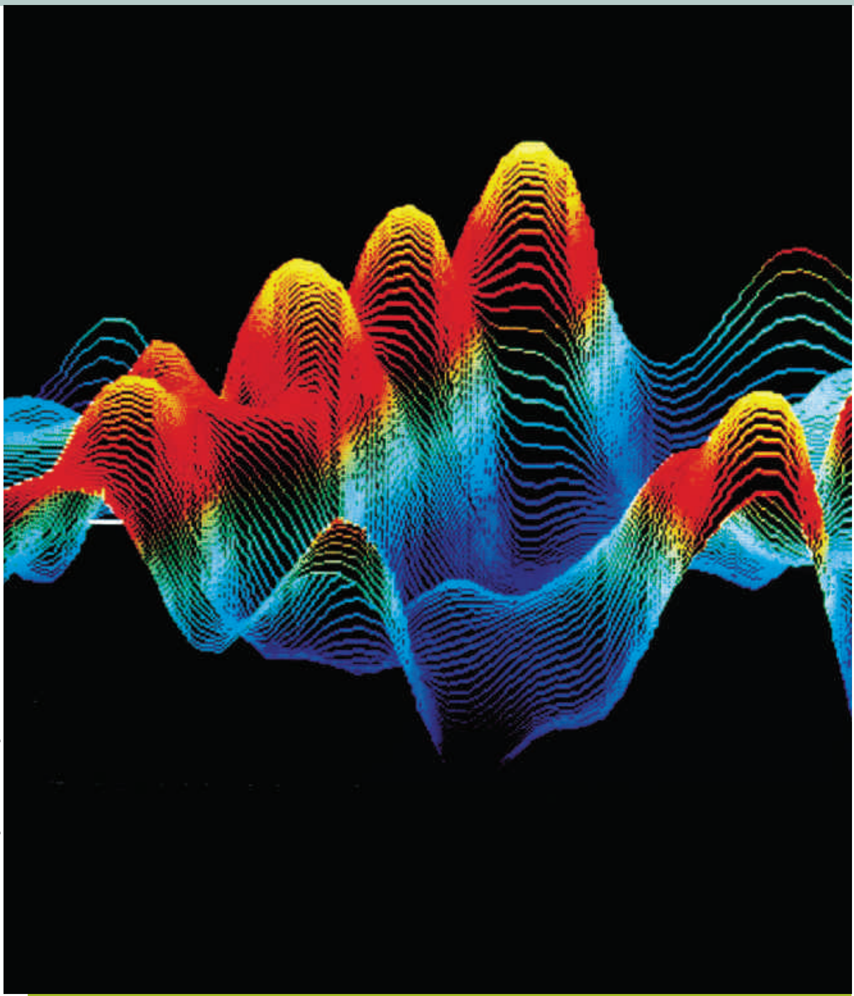
89. The sum of the angles of a triangle drawn on the surface of a sphere is greater than 180 degrees. What is the largest possible sum? What does this triangle look like?

90. The ratio of the circumference to the diameter of a circle drawn on a flat surface is 3.14. What is the value of this ratio if the circle is Earth's equator? In this case, the center of the circle is the North Pole, as shown in the following figure.



The Big Picture

The Search for Atoms



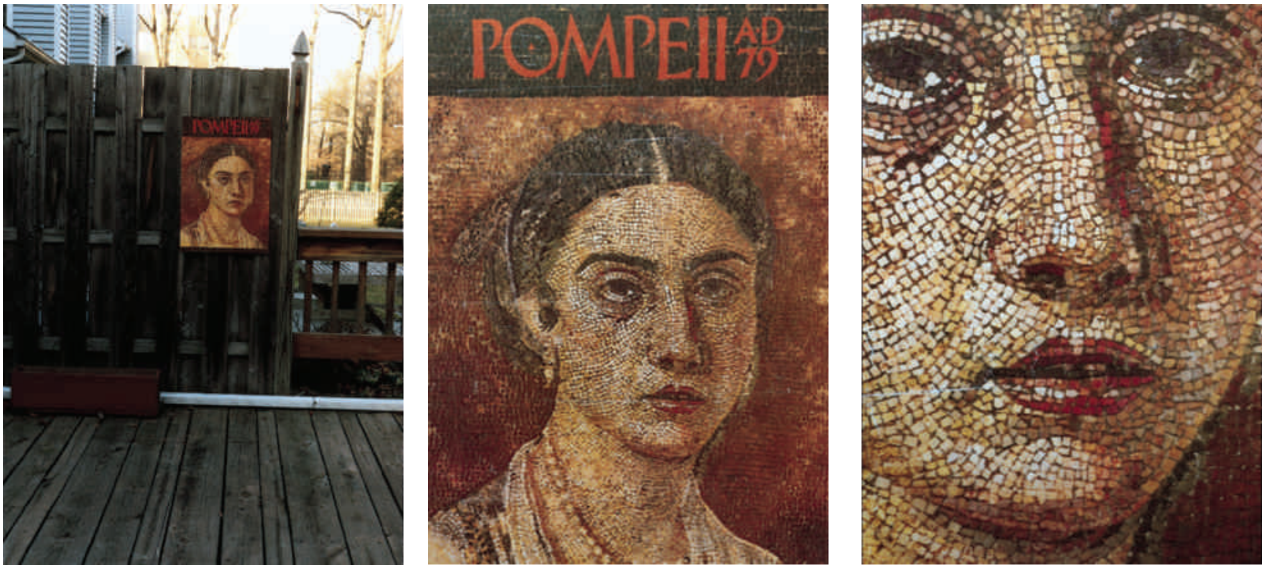
© Lawrence Berkeley Laboratory/SPL/Photo Researchers, Inc.

A sample of DNA as seen through a scanning tunneling micrograph.

One of the oldest challenges in building a physics world view is the search for the fundamental building blocks of matter. This search began more than 2000 years ago. The first ideas appeared in writings about the Greek philosopher Leucippus, who lived in the 5th century BC. Leucippus asked a simple question: "If you take a piece of gold and cut it in half and then cut one of the halves in half, and so on, will you always have gold?" We know what happens initially: one piece of gold yields two pieces of gold; either of these pieces yields two more pieces of gold; and so on. But what if you could continue the process indefinitely? Do you think you would eventually reach an end—a place where either you couldn't cut the piece or, if you could, you would no longer have gold?

Leucippus and his student Democritus felt that this process would eventually stop—that gold has a definite elementary building block. Once you get to this level, further cuts either fail or yield something different. These elementary building blocks were (and still are) known as *atoms*—from the Greek word for "indivisible."

We know of these two early atomists through the writings of Aristotle in the 4th century BC. Aristotle disagreed with their atomistic view. He realized that if matter were made of atoms, one needed to ask, "What is between them?" Presumably nothing. But Aristotle felt that a void—pure nothingness—between pieces of matter was philosophically unacceptable. Furthermore, the atomistic view held that the atoms were eternal and in continual motion. Aristotle felt this was foolish and in total con-



Courtesy of Marc Sherman (all)

As we view the woman's face from closer and closer, we begin to see the building blocks that form the image. Can we do the same for the building blocks of our material world?

flict with everyday experience. He saw a world where all objects wear out and where their natural motion is one of rest: even if pushed, they quickly slow down and stop when the pushing stops.

Above all, Aristotle believed that everything must have a purpose, a goal toward which it is directed. If these atoms whirled about in empty space, what was their purpose? Atoms seemed to defy the natural view of the universe that there was a goal to creation.

Aristotle's arguments were powerful, and his world view remained relatively unchanged for the next 19 centuries. Galileo's idea of inertia and the possibility of perpetual motion in the absence of friction did not occur until the 17th century. The technology for making a good vacuum—Aristotle's unacceptable void—did not occur until later. But eventually Aristotle's two impossibilities became possible.

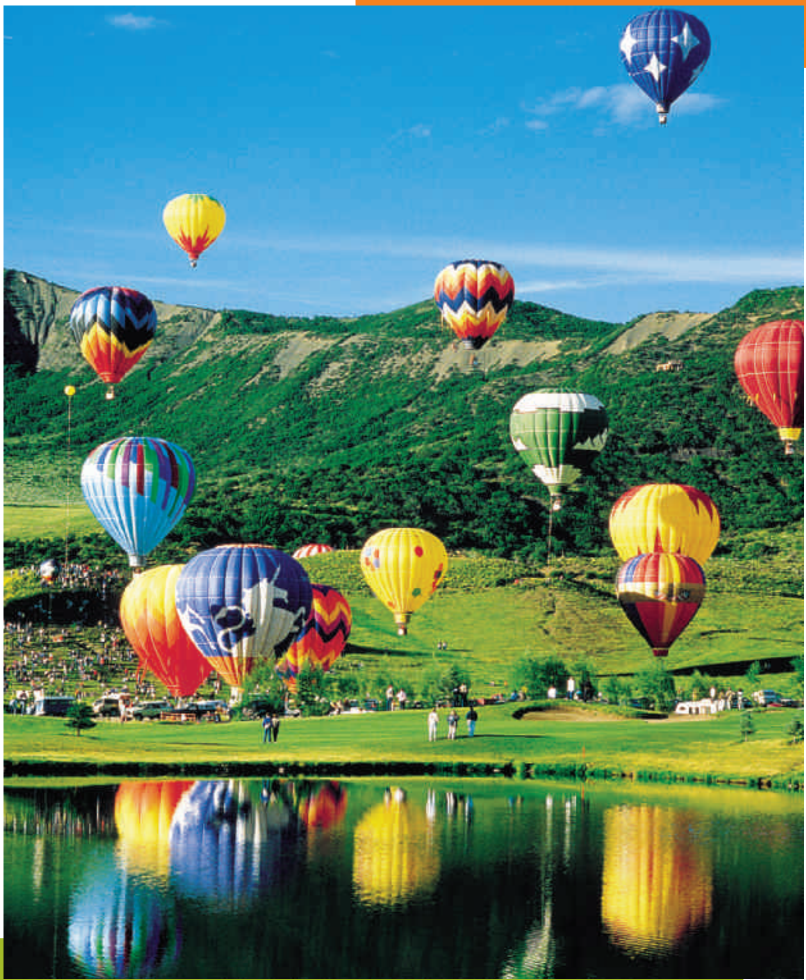
Although the evidence of atoms has grown tremendously during the last 300 years, it may be surprising to learn that the first proof of the existence of atoms didn't come until 1905. In that year, Albert Einstein published a paper showing that atoms in continual, random motion could explain a strange jiggling motion of microscopic objects suspended in fluids observed by a Scottish botanist, Robert Brown, almost 80 years earlier. Not until recently have new electron microscopes been able to show direct evidence of atoms.

Different combinations and arrangements of a relatively small number of atoms make up the diverse material world around us. What are the properties of these solids, liquids, and gases? How are their macroscopic properties, such as mass, volume, temperature, pressure, and elasticity, related to the underlying microscopic properties? We will examine both macroscopic and microscopic properties and their connections in the next two chapters. This study will then allow us to expand our understanding of one of the most fundamental concepts in the physics world view: the conservation of energy.

11 Structure of Matter

▶Hot air allows balloonists to enjoy the scenery from a high vantage point. But what do the macroscopic properties of gases—volume, pressure, and temperature—tell us about the existence of atoms and molecules and their microscopic properties of size, mass, and speed?

(See page 235 for the answer to this question.)

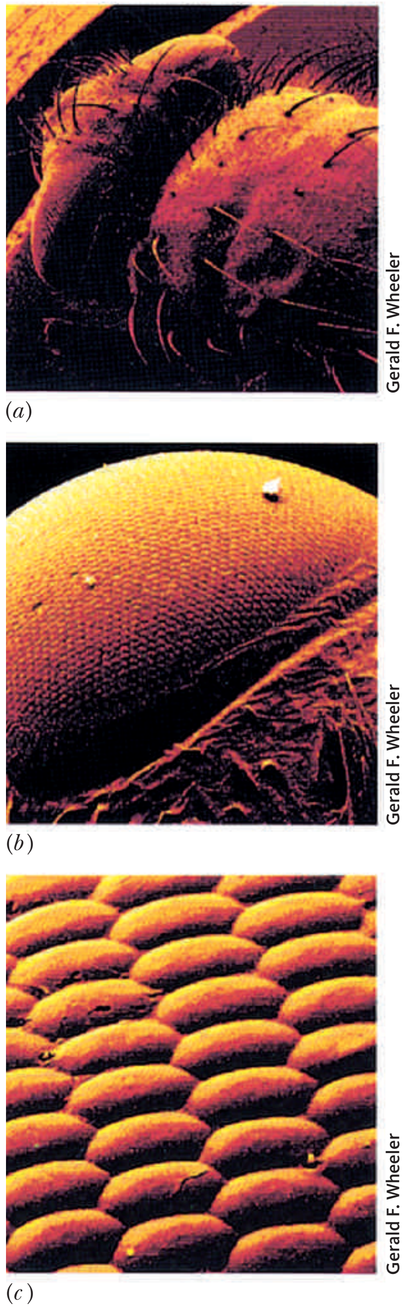


James Randklev/Stone/Getty Images

Hot-air balloons are a beautiful illustration of the ideal gas law.

WHEN we talk about the properties of objects, we usually think about their bulk, or **macroscopic**, properties such as size, shape, mass, color, surface texture, and temperature. For instance, a gas has mass, occupies a volume, exerts a pressure on its surroundings, and has a temperature. But a gas is composed of particles that have their own characteristics, such as velocity, momentum, and kinetic energy. These are the **microscopic** properties of the gas. It seems reasonable that connections should exist between these macroscopic and microscopic properties. At first glance, you may assume that the macroscopic properties are just the sum, or maybe the average, of the microscopic ones; however, the connections provided by nature are much more interesting.

We could begin our search for the connections between the macroscopic and the microscopic by examining a surface with a conventional microscope and discovering that rather than being smooth, as it appears to the naked eye, the surface has some texture. The most powerful electron microscope shows even more structure than an optical microscope reveals. But until recently, instruments could not show us the basic underlying structure of things. To gain an understanding of matter at levels beyond which they could observe directly, scientists constructed models of various possible microscopic structures to explain their macroscopic properties.



An electron micrograph of (a) a fly's head (27×) and its eye at (b) 122× and (c) 1240×.

Building Models

By the middle of the 19th century, the body of chemical knowledge had pretty well established the existence of **atoms** as the basic building blocks of matter. All the evidence was indirect but was sufficient to create some idea of how atoms combine to form various substances. This description of matter as being composed of atoms is a model. It is not a model in the sense of a scale model, such as a model railroad or an architectural model of a building, but rather a theory or mental picture.

To illustrate this concept of a model, suppose someone gives you a tin can without a label and asks you to form a mental picture of what may be inside. Suppose you hear and feel something sloshing when you shake the can. You guess that the can contains a liquid. Your model for the contents is that of a liquid, but you do not know whether this model actually matches the contents. For example, it is possible (but unlikely) that the can contains an electronic device that imitates sloshing sounds. However, you can use your knowledge of liquids to test your model. You know, for example, that liquids freeze. Therefore, your model predicts that cooling the can would stop the sloshing sounds. In this way you can use your model to help you learn more about the contents. The things you can say, however, are limited. For example, there is no way to determine the color of the liquid or its taste or smell.

Sometimes a model takes the form of an analogy. For example, the flow of electricity is often described in terms of the flow of water through pipes. Similarly, little, solid spheres might be analogous to atoms. We could use the analogy to develop rules for combining these spheres and learn something about how atoms combine to form molecules. However, it is important to distinguish between a collection of atoms that we cannot see and the spheres that we can see and manipulate. Sooner or later the analogy breaks down because electricity is not water and atoms are not tiny spheres.

Sometimes a model takes the form of a mathematical equation. Physicists have developed equations that describe the structure and behavior of atoms. Although mathematical models can be abstract, they can also be accurate descriptions of the way nature behaves. Suppose that in examining a tin can you hear a sliding sound followed by a clunk whenever you tilt the can. You predict that the can contains a metal rod. You may devise an equation for the length of time it takes a rod of a certain length to slide along the wall before hitting an end. This mathematical model would allow you to predict the time delays for different-length rods.

Regardless of its form, a model should summarize and account for the known data. It must agree with the way nature behaves. And to be useful, it must also be able to make predictions about new situations. The model for the contents of the tin can allows you to predict that liquid will flow out of the can if it is punctured. Our model for the structure of matter must allow us to make predictions that can be tested by experiment. If the predictions are borne out, they strengthen our belief in the model. If they are not borne out, we must modify our model or abandon it and invent a new one.

Early Chemistry

Experimental techniques, as opposed to careful observation, became of increasing interest to scientists around the end of the first millennium. They flourished especially in the Arabic-speaking world, where so many protochemical ideas found a home. We now unconsciously use many chemical terms—*alcohol, alchemy, alembic,* and so on—that derive from Arabic.

Alchemy was the search for the magic formula for perpetual life—the elixir (note again the Arabic)—and for the secret of how to make gold. Alchemists set the stage for our modern atomic world view, but their contributions are often overlooked. We hear only that these strange pseudoscientists spent all their time foolishly trying to turn lead into gold. But they weren't so strange. In the Aristotelian world view that all matter was composed of various proportions of four elements—earth, water, fire, and air—and that matter was continuous, it made sense that different materials could be made by changing the proportions of the four elementary substances. Making solutions and heating materials were natural beginnings because water and fire were two of the elements. A cooked egg was not the same as a raw one. Adding fire changed its characteristics. Adding fire to other materials released some air even though the original material gave no hint of containing air. Adding water to sugar changed it from a white solid to a clear liquid. This kind of experimentation—heating, dissolving in water, stirring, blending, grinding, and so on—was the work of the alchemists.

This early 19th-century Japanese woodcut shows an artisan extracting copper from its ore.

But the alchemists' role in the building of our world view was more than just finding ways of manipulating materials. By showing that the common materials were not all that existed, alchemists set the stage for the experimenters who followed. These new experimenters began with a different background of knowledge, a different common sense about the world, and a different expectation of what was possible. They went beyond cataloging ways of manipulating substances and began considering the structures of matter that could be causing these results—they built models. Although it is difficult to pinpoint the transition from alchemy to chemistry, the early chemists were part of the Newtonian age and had a different way of looking at the world. Isaac Newton himself spent many arduous hours in a little wooden laboratory outside his rooms at Trinity College, Cambridge, performing alchemical experiments.

By the latter half of the 17th century, the existence of the four Aristotelian elements was in doubt. They were of little or no help in making sense out of the chemical data that had been accumulated. However, the idea that all matter was composed of some basic building blocks was so appealing that it persisted. This belief fueled the development of our modern atomic model of matter.

The simplest, or most elementary, substances were known as **elements.** These elements could be combined to form more complex substances, the

Table 11–1 *Lavoisier's List of the Elements (1789)*

Lavoisier's Name	Modern English Name	Lavoisier's Name	Modern English Name
Lumiere	Light*	Etain	Tin
Calorique	Heat*	Fer	Iron
Oxygene	Oxygen	Manganese	Manganese
Azote	Nitrogen	Mercure	Mercury
Hydrogene	Hydrogen	Molybdene	Molybdenum
Soufre	Sulfur	Nickel	Nickel
Phosphore	Phosphorus	Or	Gold
Carbone	Carbon	Platine	Platinum
Radical muriatique†	—	Plomb	Lead
Radical fluorique†	—	Tungstene	Tungsten
Radical boracique†	—	Zinc	Zinc
Antimoine	Antimony	Chaux	Calcium oxide (lime)‡
Argent	Silver	Magnésie	Magnesium oxide‡
Arsenic	Arsenic	Baryte	Barium oxide‡
Bismuth	Bismuth	Alumina	Aluminum oxide‡
Cobalt	Cobalt	Silice	Silicon dioxide (sand)‡
Cuivre	Copper		

*Not elements.
†No elements with these properties have ever been found.
‡These "elements" are really compounds.

compounds. By the 1780s, French chemist and physicist Antoine Lavoisier and his contemporaries had enough data to draw up a tentative list of elements (Table 11-1). Something was called an element if it could not be broken down into simpler substances. (The modern periodic table of the elements is printed on the inside front cover of this book.)

A good example of an incorrectly identified element is water. It was not known until the end of the 18th century that water is a compound of the elements hydrogen and oxygen. Hydrogen had been crudely separated during the early 16th century, but oxygen was not discovered until 1774. When a flame is put into a test tube of hydrogen, it "pops." One day while popping hydrogen, an experimenter noticed some clear liquid in the tube. This liquid was water. This was the first hint that water was not an element. The actual decomposition of water was accomplished at the end of the 18th century by a technique known as *electrolysis,* in which an electric current passing through a liquid or molten compound breaks it down into its respective elements.

The radically different properties of elements and their compounds are still striking in the modern world view. Hydrogen, an explosive gas, and oxygen, the element required for all burning, combine to form a compound that is great for putting out fires! Similarly, sodium, a very reactive metal that must be kept in oil to keep it from reacting violently with moisture in the air, combines with chlorine, a poisonous gas, to form a compound that tastes great on mashed potatoes—common table salt!

The electrolysis of water breaks up the water molecules into hydrogen and oxygen. Notice that the volume of hydrogen collected in the right-hand tube is twice that of the oxygen collected in the left-hand tube.

Q: Could these early chemists know for sure that a substance was an element?

A: They never really knew whether the substance was an element or whether they had not yet figured out how to break it down.

Are You On the Bus?

Chemical Evidence of Atoms

Another important aspect of elements and compounds was discovered around 1800. Suppose a particular compound is made from two elements and when you combine 10 grams of the first element with 5 grams of the second, you get 12 grams of the compound and have 3 grams of the second element remaining. If you now repeat the experiment, only this time adding 10 grams of each element, you still get 12 grams of the compound, but now have 8 grams of the second element remaining. This result was exciting. It meant that, rather than containing some random mixture of the two elements, the compound had a definite ratio of their masses. This principle is known as the **law of definite proportions.**

Q: How much of the compound would you get if you added only 1 gram of the second element?

A: Because 10 grams of the first element require 2 grams of the second, 1 gram of the second will combine with 5 grams of the first. The total mass of the compound is just the sum of the masses of the two elements, so 6 grams of the compound will be formed.

This law is difficult to explain using the Aristotelian model, which viewed matter as a continuous, smooth substance. In the continuum model, one would expect a range of masses in which the elements could combine to form the compound. An atomic model, on the other hand, provides a simple explanation: The atoms of one element can combine with atoms of another element to form **molecules** of the compound. It may be that one atom of the first element combines with one atom of the second to form one molecule of the compound, which contains two atoms. Or it may be that one atom of the first element combines with two atoms of the second element. In any case the ratio of the masses of the combining elements has a definite value. (Note that the value of the ratio doesn't change with differing amounts. The mass ratio of 10 baseballs and 10 basketballs is the same as that of 1 baseball and 1 basketball. It doesn't matter how many balls we have as long as there is one baseball for *each* basketball.)

The actual way in which the elements combined and what caused them to always combine in the same way was unknown. English mathematician and physicist John Dalton hypothesized that the elements might have hooks (Figure 11-1) that control how many of one atom combine with another. Dalton's hooks can be literal or metaphorical; the actual mechanism is not important.

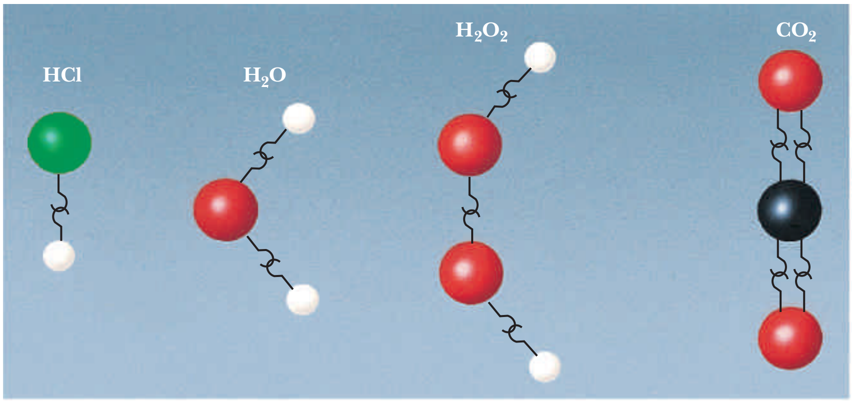


Figure 11-1 Dalton's atomic model used hooks to explain the law of definite proportions.

The essential point of his model was that different atoms have different capacities for attaching to other atoms. Regardless of the visual model we use, atoms combine in a definite ratio to form molecules. One atom of chlorine combines with one atom of sodium to form salt. The ratio in salt is always one atom to one atom.

In retrospect it may seem that the law of definite proportions was a minor step and that it should have been obvious once mass measurements were made. However, seeing this relationship was difficult because some processes did not obey this law. For instance, *any* amount of sugar (up to some maximum) dissolves completely in water. One breakthrough came when it was recognized that this process was distinctly different. The sugar–water solution was not a compound with its own set of properties but simply a mixture of the two substances. Mixtures had to be recognized as different from compounds and eliminated from the discussion.

Another complication occurred because some elements can form more than one compound. Carbon atoms, for example, could combine with one or two oxygen atoms to form two compounds with different characteristics. When this happened in the same experiment, the final product was not a pure compound but a mixture of compounds. This result yielded a range of mass ratios and was quite confusing until chemists were able to analyze the compounds separately.

Fortunately, the atomic model makes predictions about situations in which two elements form more than one compound. Imagine for a moment that atoms can be represented by nuts and bolts. Suppose a hypothetical molecule of one compound consists of one nut and one bolt and another consists of two nuts and one bolt. Because there are twice as many nuts for each bolt in the second compound (Figure 11-2), it has a mass ratio of nuts to bolts that is twice that of the first compound. This prediction was confirmed for actual compounds and provided further evidence for the existence of atoms.

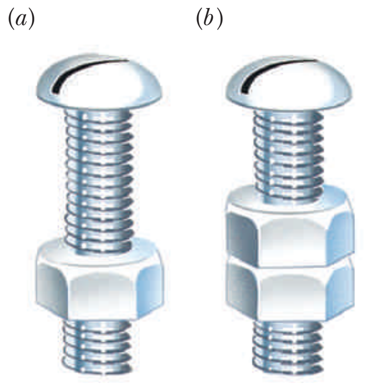


Figure 11-2 A simple model of two compounds: (a) "bolt-mononut" and (b) "bolt-dinut." The ratio of the mass of nuts to the mass of bolts is twice as large for "bolt-dinut."

Masses and Sizes of Atoms

Extended presentation available in the *Problem Solving* supplement

Even with their new information, the 18th-century chemists did not know how many atoms of each type it took to make a specific molecule. Was water composed of one atom of oxygen and one atom of hydrogen, or was it one atom of oxygen and two atoms of hydrogen, or two of oxygen and one of hydrogen? All that was known was that 8 grams of oxygen combined with 1 gram of hydrogen. These early chemists needed to find a way to establish the relative masses of atoms.

The next piece of evidence was an observation made when gaseous elements were combined; the gases combined in definite *volume* ratios when their temperatures and pressures were the same. This statement was not surprising except that the volume ratios were always simple fractions. For example, 1 liter of hydrogen combines with 1 liter of chlorine (a ratio of 1 to 1), 1 liter of oxygen combines with 2 liters of hydrogen (a ratio of 1 to 2), 1 liter of nitrogen combines with 3 liters of hydrogen (a ratio of 1 to 3), and so on (Figure 11-3).

It was tempting to propose an equally simple underlying rule to explain these observations. Italian physicist Amedeo Avogadro suggested that under identical conditions, each liter of any gas contains the same number of molecules. Although it took more than 50 years for this hypothesis to be accepted, it was the key to unraveling the question of the number of atoms in molecules.

Once the number of atoms in each molecule was known, the data on the mass ratios could be used to calculate the relative masses of different atoms. For example, an oxygen atom has about 16 times the mass of a hydrogen atom.

Figure 11-3 Gases combine completely to form compounds when the ratios of their volumes are equal to the ratios of small whole numbers. One liter of nitrogen combines completely with 3 liters of hydrogen to form 2 liters of ammonia.

Q: Given that oxygen and hydrogen gases are both composed of molecules with two atoms each, how many atoms of oxygen and hydrogen combine to form water?

A: The observation that 2 liters of hydrogen gas combine with 1 liter of oxygen means that there are two hydrogen molecules for each oxygen molecule. Therefore, there are four hydrogen atoms for every two oxygen atoms. The simplest case would be for these to form two water molecules with two hydrogen atoms and one oxygen atom in each water molecule. This is confirmed by the observation that 2 liters of water vapor are produced.

To avoid the use of ratios, a mass scale was invented by choosing a value for one of the elements. An obvious choice was to assign the value of 1 to hydrogen because it is the lightest element. However, setting the value of carbon equal to 12 **atomic mass units** (amu) makes the relative masses of most elements close to whole-number values. These values are known as **atomic masses** and keep the value for hydrogen very close to 1. Even though the values for the actual atomic masses are now known, it is still convenient to use the relative atomic masses.

Q: What is the atomic mass of carbon dioxide, a gas formed by combining two oxygen atoms with each carbon atom?

A: We have 12 atomic mass units for the carbon atom and 16 atomic mass units for each oxygen atom. Therefore, 12 atomic mass units + 32 atomic mass units = 44 atomic mass units.

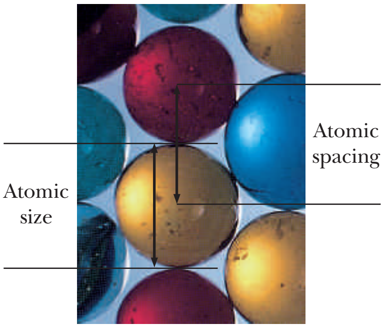


Figure 11-4 Assuming that the atoms are "touching" like marbles, the spacing between their centers is the same as their diameters.

The problem of determining the masses and diameters of individual atoms required the determination of the number of atoms in a given amount of material. Diffraction experiments, like those described in Chapter 19 but using X rays, determined the distance between individual atoms in solids to be about 10^{-10} meter, one 10-billionth of a meter. If we assume that atoms in a solid can be represented by marbles like those in Figure 11-4, the diameter of an atom is about equal to their spacing. This means that it would take 10 billion atoms to make a line 1 meter long. Stated another way, if we imagine expanding a baseball to the size of Earth, the individual atoms of the ball would only be the size of grapes!

A useful quantity of matter for our purposes is the **mole.** If the mass of the molecule is some number of atomic mass units, 1 mole of the substance is this same number of grams. For example, 1 mole of carbon is 12 grams. Further experiments showed that 1 mole of any substance contains the same number of molecules—namely, 6.02×10^{23} molecules, a number known as **Avogadro's number.** With this number we can calculate the size of the atomic mass unit in terms of kilograms. Because 12 grams of carbon contain Avogadro's number of carbon atoms, the mass of one atom is

$$m_{carbon} = \frac{12 \text{ g}}{6.02 \times 10^{23} \text{ molecules}} = 2 \times 10^{-23} \text{ g/molecule}$$

Because one carbon atom also has a mass of 12 atomic mass units, we obtain

$$\frac{2 \times 10^{-23} \text{ g}}{12 \text{ amu}} = 1.66 \times 10^{-24} \text{ g/amu}$$

Therefore, 1 atomic mass unit equals 1.66×10^{-27} kilogram, a mass so small that it is hard to imagine. This is the approximate mass of one hydrogen atom. The most massive atoms are about 260 times this value.

FLAWED REASONING

Two students are arguing after class about ideal gases.

Hyrum: "If two ideal gases are both at the same temperature and pressure, then equal volumes will contain equal numbers of atoms. This means that 1 mole of ammonia (NH_3) would take up twice as much volume as 1 mole of nitrogen (N_2) because each ammonia molecule has four atoms and each nitrogen molecule has only two."

Brielle: "No, equal volumes will contain equal numbers of *molecules,* not *atoms.* One mole of ammonia would contain the same number of molecules as 1 mole of nitrogen—namely, Avogadro's number—so they would take up the same volume."

Do you agree with either of these students?

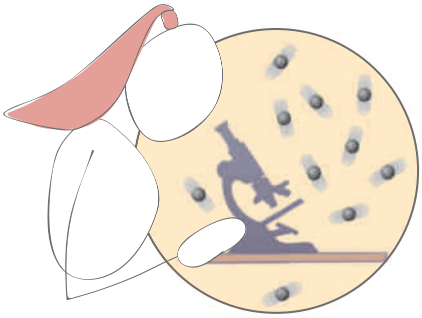
ANSWER Brielle was paying attention in class. Avogadro found that the number of molecules determined the volume of a gas for a given temperature and pressure. The number of atoms in each molecule does not matter.

The Ideal Gas Model

Many macroscopic properties of materials can be understood from the atomic model of matter. In many situations the behavior of real gases is closely approximated by an **ideal gas.** The gas is assumed to be composed of an enormous number of tiny particles separated by relatively large distances. These particles are assumed to have no internal structure and to be indestructible. They also do not interact with each other except when they collide, and then they undergo elastic collisions much like air-hockey pucks. Although this model may not seem realistic, it follows in the spirit of Galileo in trying to get at essential features. Later we can add the complications of real gases.

For this model to have any validity, it must describe the macroscopic behavior of gases. For instance, we know that gases are easily compressed. This makes sense; the model says that the distance between particles is much greater than the particle size, and they don't interact at a distance. There is, then, a lot of space in the gas, and it should be easily compressed. This aspect of the model also accounts for the low mass-to-volume ratio of gases.

Because a gas completely fills any container and the particles are far from one another, the particles must be in continual motion. Is there any other evidence that the particles are continually moving? We may ask, "Is the air in the room moving even with all the doors and windows closed to eliminate drafts?" The fact that you can detect an open perfume bottle across the room indicates that some of the perfume particles have moved through the air to your nose.



Pollen grains suspended in a liquid exhibit continual, erratic motion known as Brownian motion.

More direct evidence for the motion of particles in matter was observed in 1827 by Scottish botanist Robert Brown. To view pollen under a microscope without it blowing away, Brown mixed the pollen with water. He discovered that the pollen grains were constantly jiggling. Brown initially thought that the pollen might be alive and moving erratically on its own. However, he observed the same kind of motion with inanimate objects as well.

Brownian motion is not restricted to liquids. Observation of smoke under a microscope shows that the smoke particles have the same erratic motion. This motion never ceases. If the pollen and water are kept in a sealed container and put on a shelf, you would still observe the motion years later. The particles are in continual motion.

It was 78 years before Brownian motion was rigorously explained. Albert Einstein demonstrated mathematically that the erratic motion was due to collisions between water molecules and pollen grains. The number and direction of the collisions occurring at any time is a statistical process. When the collisions on opposite sides have equal impulses, the grains are not accelerated. But when more collisions occur on one side, the pollen experiences an abrupt acceleration that is observed as Brownian motion.

Pressure

Let's take a look at one of the macroscopic properties of an ideal gas that is a result of the atomic motions. **Pressure** is the force exerted on a surface divided by the area of the surface—that is, the force per unit area:

$$\text{pressure} = \frac{\text{force}}{\text{area}}$$

$$P = \frac{F}{A}$$

This definition is not restricted to gases and liquids. For instance, if a crate weighs 6000 newtons and its bottom surface has an area of 2 square meters, what pressure does it exert on the floor under the crate?

$$P = \frac{F}{A} = \frac{6000 \text{ N}}{2 \text{ m}^2} = 3000 \text{ N/m}^2$$

Therefore, the pressure is 3000 newtons per square meter. The SI unit of pressure [newton per square meter (N/m^2)] is called a pascal (Pa). Pressure in the U.S. customary system is often measured in pounds per square inch (psi) or atmospheres (atm), where 1 atmosphere is equal to 101 kilopascals or 14.7 pounds per square inch.

Q: Susan asks politely whether it would be all right with you if she pushes on your arm with a force of 5 newtons (about 1 pound). Should you let her?

A: That depends. If she pushes on your arm with the palm of her hand, you will hardly notice a force of 5 newtons. If, on the other hand, she pushes on your arm with a sharp hatpin, you will definitely notice! The damage to your arm does not depend on the force but on the pressure.

Imagine a cubic container of gas in which particles are continually moving around and colliding with each other and with the walls (Figure 11-5). In each collision with a wall, the particle reverses its direction. Assume a head-on collision as in the case of the yellow particle in Figure 11-5. (If the collision is a glancing blow, only the component of the velocity perpendicular to the wall would be reversed.) This means that its momentum is also reversed. The change in momentum means that there must be an impulse on the particle and an equal and opposite impulse on the wall (Chapter 6). Our model assumes that an enormous number of particles strike the wall. The average of an enormous number of impulses produces a steady force on the wall that we experience as the pressure of the gas.

We can use this application of the ideal gas model to make predictions that can be tested. Suppose, for example, that we shrink the volume of the container. This means that the particles have less distance to travel between collisions with the walls and should strike the walls more frequently, increasing the pressure. Therefore, decreasing the volume increases the pressure, provided that the average speeds of the molecules do not change. Similarly, if we increase the number of particles in the container, we expect the pressure to increase because there will be more frequent collisions with the walls.

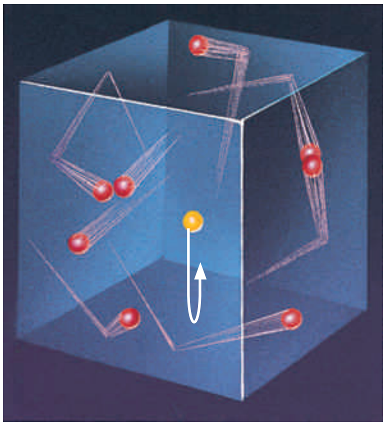


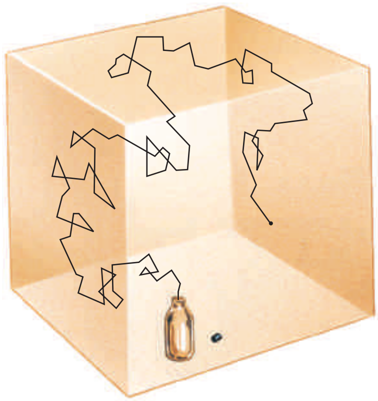
Figure 11-5 Gas particles are continually colliding with each other and with the walls of the container.

Atomic Speeds and Temperature

Presumably, the atomic particles making up a gas have a range of speeds due to their collisions with the walls and with each other. The distribution of these speeds can be calculated from the ideal gas model and a connection made with temperature. Therefore, a direct measurement of these speeds would provide additional support for the model. This is not an easy task. Imagine trying to measure the speeds of a large group of invisible particles. One needs to devise a way of starting a race and recording the order of the finishers.

One creative approach led to a successful experiment in 1920. The gas leaves a heated vessel and passes through a series of small openings that select only those particles going in a particular direction [Figure 11-6(a)]. Some of these particles enter a small opening in a rapidly rotating drum, as shown in Figure 11-6(b). This arrangement guarantees that a group of particles start across the drum at the same time. Particles with different speeds take different times to cross the drum and arrive on the opposite wall after the drum has rotated by different amounts. The locations of the particles are recorded by a film of sensitive material attached to the inside of the drum [Figure 11-6(d)]. A drawing of the film's record is shown in Figure 11-7(a). A graph of the number of particles versus their position along the film is shown in Figure 11-7(b).

Most of the particles have speeds near the average speed, but some move very slowly and some very rapidly. The average speed is typically about 500 meters per second, which means that an average gas particle could travel the length of five football fields in a single second. This high value may seem counter to your experience. If the particles travel with this speed, why does it take several minutes to detect the opening of a perfume bottle on the other side of the room? This delay is due to collisions between the gas particles. On average a gas particle travels a distance of only 0.0002 millimeter before it collides with another gas particle. (This distance is about 1000 particle diameters.) Each particle makes approximately 2 billion collisions per second. During these collisions the particles can radically change directions, resulting in zigzag paths. So although their average speed is quite fast, it takes them a long time to cross the room because they travel enormous distances.



Atomic particles in air travel in zigzag paths because of numerous collisions with air molecules.

When the speeds of the gas particles are measured at different temperatures, something interesting is found. As the temperature of the gas increases, the speeds of the particles also increase. The distributions of speeds for three temperatures are given in Figure 11-8. The calculations based on the model

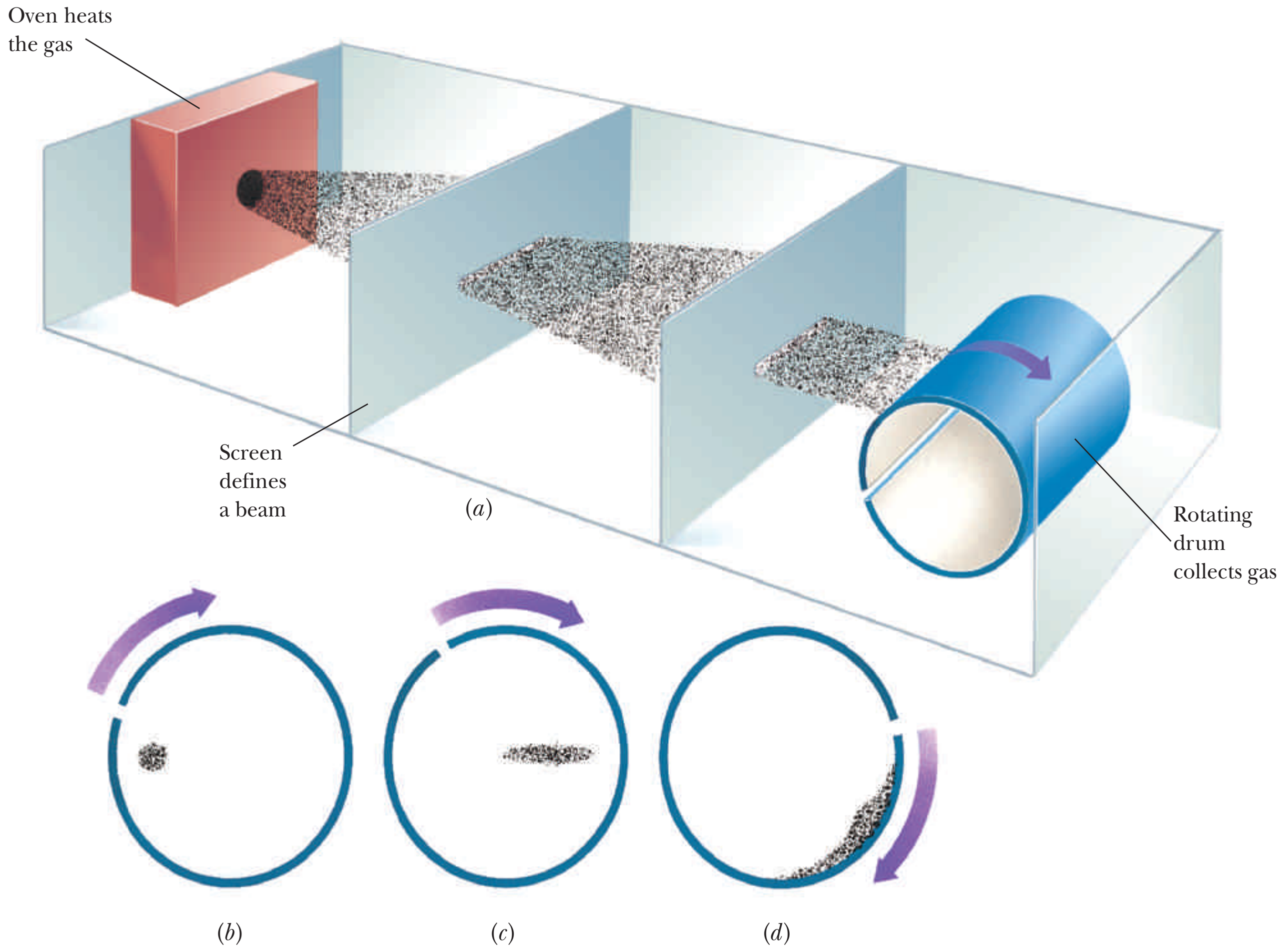


Figure 11-6 (a) An apparatus for measuring the speeds of atomic particles in a gas. (b) A small bunch of particles enters the rotating drum through the narrow slit. (c) The particles spread out as they move across the drum because of their different speeds. (d) The particles are deposited on a sensitive film at locations determined by how much the drum rotates before they arrive at the opposite wall.

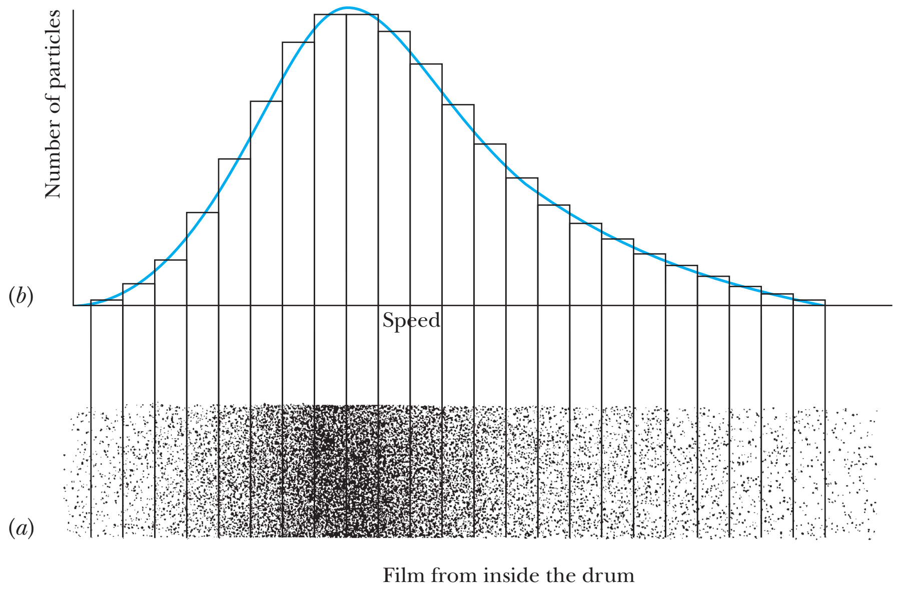


Figure 11-7 (a) The distribution of atomic particles as recorded by the film along the circumference of the drum. (b) The distribution of atomic speeds calculated from this experiment.

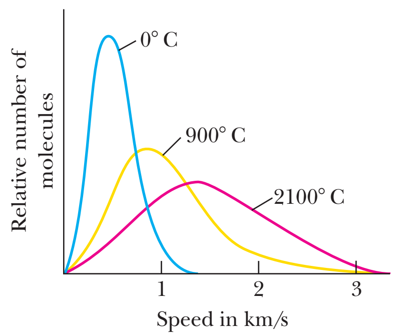


Figure 11-8 The distribution of atomic speeds changes as the temperature of the gas changes.

agree with these results. A relationship can be derived that connects temperature, a macroscopic property, with the average kinetic energy of the gas particles, a microscopic property. However, the simplicity of this relationship is apparent only with a particular temperature scale.

Temperature

We generally associate temperature with our feelings of hot and cold; however, our subjective feelings of hot and cold are not very accurate. Although we can usually say which of two objects is hotter, we can't state just how hot something is. To do this we must be able to assign numbers to various temperatures.

Assigning numbers to various temperatures turns out to be a difficult task that has occupied some of the greatest scientific minds. Just as it is not possible to define time in a simple way, it is not possible to define temperature in a simple way. In Chapters 12 through 14, we will return to the subject of temperature a number of times with the aim of helping you incorporate the concept of temperature into your world view. We start with a familiar concept: measuring temperature with a thermometer.

Galileo was the first person to develop a thermometer. He observed that some of an object's properties change when its temperature changes. For example, with only a few exceptions, when an object's temperature goes up, it expands. Galileo's thermometer (Figure 11-9) was an inverted flask with a little water in its long neck. As the enclosed air got hotter, it expanded and forced the water down the flask's neck. Conversely, the air contracted on cooling, and the water rose. Galileo completed his thermometer by marking a scale on the neck of the flask.

Unfortunately, the water level also changed when atmospheric pressure changed. The alcohol-in-glass thermometer, which is still popular today, replaced Galileo's thermometer. The column is sealed so that the rise and fall of the alcohol is due to its change in volume and not the atmospheric pressure. The change in height is amplified by adding a bulb to the bottom of the column, as shown in Figure 11-10. When the temperature rises, the larger volume in the bulb expands into the narrow tube, making the expansion much more obvious.

In 1701 Newton proposed a method for standardizing the scales on thermometers. He put the thermometer in a mixture of ice and water, waited for the level of the alcohol to stop changing, and marked this level as zero. He used the temperature of the human body as a second fixed temperature, which he called 12. The scale was then marked off into 12 equal divisions, or degrees.

Shortly after this, German physicist Gabriel Fahrenheit suggested that the zero point correspond to the temperature of a mixture of ice and salt. Because this was the lowest temperature producible in the laboratory at that time, it avoided the use of negative numbers for temperatures. The original 12 degrees were later divided into eighths and renumbered so that body temperature became 96 degrees.

It is important that the fixed temperatures be reliably reproducible in different laboratories. Unfortunately, neither of Fahrenheit's reference temperatures could be reproduced with sufficient accuracy. Therefore, the reference temperatures were changed to those of the freezing and boiling points of pure water at standard atmospheric pressure. To get the best overall agreement with the previous scale, these temperatures were defined to be 32°F and 212°F, respectively. This is how we ended up with such strange numbers on the **Fahrenheit temperature scale.** On this scale, normal body temperature is 98.6°F.

At the time the metric system was adopted, a new temperature scale was defined with the freezing and boiling points as 0°C and 100°C. The name of this centigrade (or 100-point) scale was changed to the **Celsius temperature**

Figure 11-9 The height of the liquid in Galileo's first thermometer indicated changes in temperature.

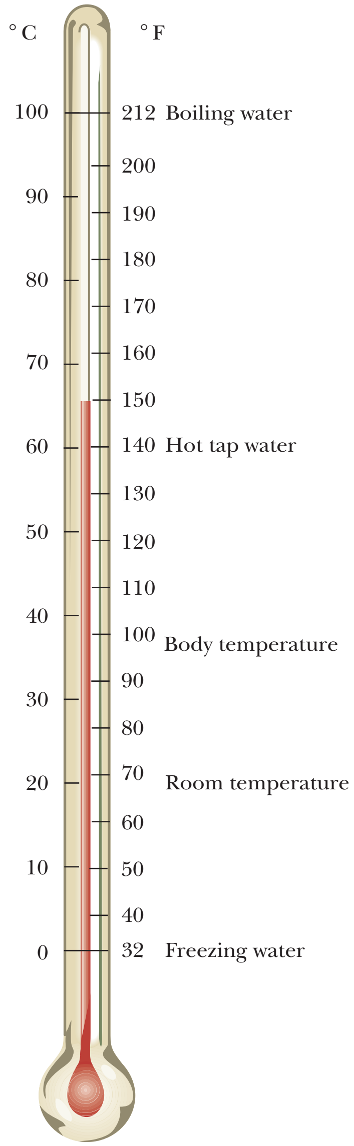


Figure 11-10 A comparison of the Fahrenheit and Celsius temperature scales.

Courtesy of Patrick Harman

The Fahrenheit and Celsius scales give the same reading at −40°.

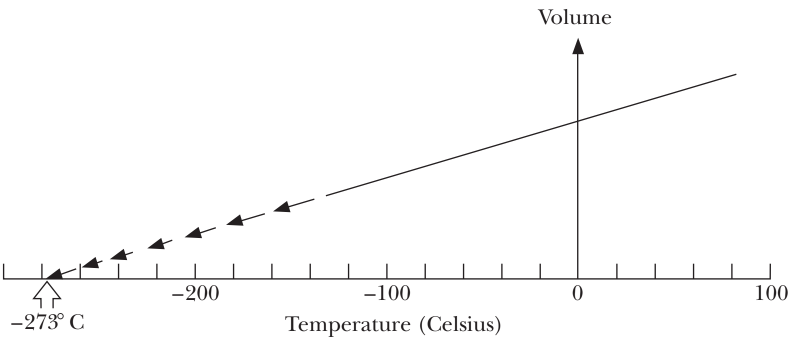
scale in 1948 in honor of Swedish astronomer Anders Celsius, who devised the scale. A comparison of the Fahrenheit and Celsius scales is given in Figure 11-10. This figure can be used to convert temperatures from one scale to the other. If the temperature outside is −40° (which sometimes happens in Montana) it does not matter which temperature scale you are using. The Celsius and Fahrenheit scales yield the same value at this temperature.

Q: What are room temperature (68°F) and body temperature (98.6°F) on the Celsius scale?

A: Using Figure 11-10, we see that room temperature is about 20°C and body temperature is about 37°C.

Assume that we have a quantity of ideal gas in a special container designed to always maintain the pressure of the gas at some constant low value. When the volume of the gas is measured at a variety of temperatures, we obtain the graph shown in Figure 11-11. If the line on the graph is extended down to the left, we find that the volume goes to zero at a temperature of −273°C

Figure 11-11 When the graph of volume versus temperature of an ideal gas is extrapolated to zero volume, the temperature scale reads −273°C.



(−459°F). Although we could not actually do this experiment with a real gas, this very low temperature arises in several theoretical considerations and is the basis for a new, more fundamental temperature scale.

The **Kelvin temperature scale,** also known as the **absolute temperature scale,** has its zero at −273°C and the same-size degree marks as the Celsius scale. The difference between the Celsius and Kelvin scales is that temperatures are 273 degrees higher on the Kelvin scale. Water freezes at 273 K and boils at 373 K. (Notice that the degree symbol is dropped from this scale. The freezing point of water is read "273 kelvin," or "273 kay.") The Kelvin scale is named for British physicist William Thomson, who is more commonly known as Lord Kelvin.

◀ K = C + 273

Q: What is normal body temperature (37°C) on the Kelvin scale?

A: Body temperature is 37 + 273 = 310 K.

It would seem that all temperature scales are equivalent and which one we use would be a matter of history and custom. It is true that these scales are equivalent because conversions can be made between them. However, the absolute temperature scale has a greater simplicity for expressing physical relationships. In particular, the relationship between the volume and temperature of an ideal gas is greatly simplified using absolute temperatures. *The volume of an ideal gas at constant pressure is proportional to the absolute temperature.* This means that if the absolute temperature is doubled while keeping the pressure fixed, the volume of the gas doubles.

The volume of an ideal gas at constant pressure can be used as a thermometer. All we need to do to establish the temperature scale is measure the volume at one fixed temperature. Of course, thermometers must be made of real gases. But real gases behave like the ideal gas if the pressure is kept low and the temperature is well above the temperature at which the gas liquefies.

This new scale also connects the microscopic property of atomic speeds and the macroscopic property of temperature. *The absolute temperature is directly proportional to the average kinetic energy of the gas particles.* This means that if we double the average kinetic energy of the particles, the absolute temperature of a gas doubles. Remember, however, that the average speed of the gas particles does not double, because the kinetic energy depends on the square of the speed (Chapter 7).

◀ T is proportional to KE_{ave}

FLAWED REASONING

When you wake, the temperature outside is 40°F, but by noon it is 80°F. **Why is it not reasonable to say that the temperature doubled?**

ANSWER The zero point for the Fahrenheit scale was arbitrarily chosen as the temperature of a mixture of ice and salt. If this zero point had been chosen differently—say, 30 degrees higher—the temperature during the morning would have changed from 10°F to 50°F, an increase of a factor of 5! Clearly, we can attach no physical significance to the doubling of the temperature reading on the Fahrenheit scale (or the Celsius scale). If, on the other hand, the temperature of a gas doubles on the Kelvin scale, we can say that the average kinetic energy of the gas particles has also doubled.

WORKING IT OUT *Constant Pressure*

An ideal gas at room temperature is contained in a cylinder by a piston that is free to move. Sand is placed on top of the piston (as shown in Figure 11-12) until the pressure of the gas is 2 atmospheres. The gas is then heated and, as the temperature is raised, the volume of the gas increases while the pressure of the gas remains constant. At what temperature will the volume of the gas be three times its initial volume?

At constant pressure, the volume of an ideal gas is directly proportional to the absolute temperature of the gas. Room temperature is 20 + 273 = 293 K. The volume of the gas will triple when the absolute temperature is tripled, at 3(293 K) = 879 K. This is a temperature of 879 − 273 = 606°C, which is 1120°F.

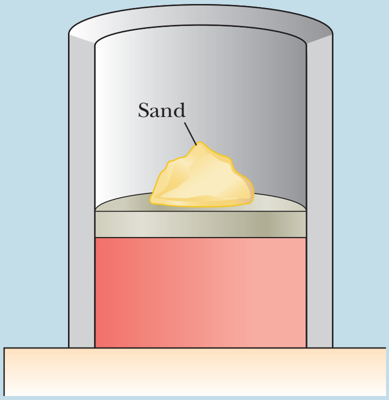


Figure 11-12 The piston is free to move, allowing the volume of the gas to change as it is heated. The pressure of the gas remains constant.

The Ideal Gas Law

The three macroscopic properties of a gas—volume, temperature, and pressure—are related by a relationship known as the **ideal gas law.** This law states that

ideal gas law ▶

$$PV = nRT$$

where P is the pressure, V is the volume, n is the number of moles, T is the *absolute* temperature, and R is a number known as the gas constant.

This relationship is a combination of three experimental relationships that had been discovered to hold for the various pairs of these three macroscopic properties. For example, if we hold the temperature of a quantity of gas constant, we can experimentally determine what happens to the pressure as we compress the gas. Or we can vary the pressure and measure the change in volume. This experimentation leads to a relationship known as *Boyle's law,* which states that the product of the pressure and the volume is a constant. This is equivalent to saying that they are inversely proportional to each other; as one increases, the other must decrease by the same factor.

In a similar manner, we can investigate the relationship between temperature and volume while holding the pressure constant. The results for a gas at one pressure are shown in Figure 11-11. As stated in the previous section, the volume in this case is directly proportional to the absolute temperature.

The third relationship is between temperature and pressure at a constant volume. The pressure in this case is directly proportional to the absolute temperature.

Each of these relationships can be obtained from our model for an ideal gas. For example, let's take a qualitative look at Boyle's law. As we decrease the volume while keeping the temperature the same, the molecules will be moving at the same average speed as before but will now hit the sides more frequently; therefore, the pressure increases in agreement with the statement of Boyle's law.

Q: How does the ideal gas model explain the rise in pressure of a gas as its temperature is raised without changing its volume?

A: Raising the temperature of the gas increases the kinetic energies of the particles. The increased speeds of the particles mean not only that they have larger momenta but also that they hit the walls more frequently.

Everyday Physics | *Evaporative Cooling*

Many of the concepts of the ideal gas model apply to liquids as well as gases. One big difference between liquids and gases is the strength of the attractive forces between the molecules. In our ideal gas model, we assumed that these forces could be neglected until the molecules collided. As a consequence a gas expands to fill its container. However, liquids have a definite volume. It is intermolecular forces that hold the molecules in the liquid together.

If we assume that a model for liquids is similar to that for gases, we can begin to understand the evaporation of liquids. Assume that the kinetic energies of the molecules in liquids have a distribution similar to that in gases and that the average kinetic energy of the particles increases with increasing temperature. The intermolecular forces perform work on molecules that try to escape the liquid, allowing only those with large enough kinetic energies to succeed. Therefore, the molecules that leave the liquid have higher-than-average kinetic energies. Conservation of energy requires that the average kinetic energy of the molecules left behind is lower, and the liquid is cooled. Water is often carried in canvas bags on desert trips to keep the water cool. The canvas bag is kept wet by water seeping through the canvas. The evaporation of the water from the wet canvas keeps the rest of the water cool.

Evaporative cooling can be demonstrated with a simple experiment. Wrap the end of a thermometer in cotton soaked in room-temperature water and observe the temperature as the water evaporates.

Your body uses evaporative cooling to maintain your body temperature on hot days or during strenuous exercise. The evaporating sweat cools our bodies. If you didn't sweat, you might die of heat prostration! A more effective way of cooling your body is the alcohol rub used to reduce fevers.

Jeff Smith/FOTOSMITH

Canvas bags like the one shown here keep water cool, even in a hot desert.

1. Why might hikers get hypothermia during wet weather even when the temperature is above freezing?
2. The temperature of boiling water does not increase even if the heat is turned on high. Use the microscopic model to explain this.

WORKING IT OUT *Ideal Gas Law*

A volume of 200 cm^3 of an ideal gas has an initial temperature of 20°C and an initial pressure of 1 atm. What is the final pressure if the volume is reduced to 100 cm^3 and the temperature is raised to 100°C?

An ideal gas in a closed container will have a fixed number of molecules. The number of moles of gas, n, will remain unchanged as temperature, volume, and pressure are varied. In this case, the ideal gas law takes the form

$$\frac{PV}{T} = nR = \text{constant}$$

This combination of pressure, volume, and absolute temperature always stays the same for the gas, so we can write

$$\frac{P_f V_f}{T_f} = \frac{P_i V_i}{T_i}$$

The initial temperature is 20 + 273 = 293 K. The final temperature is 100 + 273 = 373 K. Substituting the values given, we have

$$\frac{P_f(100\ \text{cm}^3)}{373\ \text{K}} = \frac{(1\ \text{atm})(200\ \text{cm}^3)}{293\ \text{K}}$$

The final pressure is therefore

$$P_f = (1\ \text{atm})\frac{(200\ \text{cm}^3)}{(100\ \text{cm}^3)}\frac{373\ \text{K}}{293\ \text{K}} = 2.55\ \text{atm}$$

Summary

The most elementary substances are elements, which are composed of a large number of very tiny, identical atoms. These atoms combine in definite mass ratios to form molecules according to the law of definite proportions. Observations that gaseous elements combine in definite volume ratios allowed the determination of the relative masses of different atoms. The mass of a carbon atom is set equal to 12 atomic mass units.

Modern experiments show that atoms have diameters of approximately 10^{-10} meter and masses ranging from 1 to more than 260 atomic mass units, where 1 atomic mass unit is equal to 1.66×10^{-27} kilogram.

The Celsius temperature scale is defined with the freezing and boiling points of water as 0°C and 100°C, respectively. The absolute, or Kelvin, temperature scale has its zero point at −273°C and the same-size degree as the Celsius scale.

The ideal gas model assumes that the gas is composed of an enormous number of tiny, indestructible spheres with no internal structure, separated by relatively large distances, and interacting only via elastic collisions. The pressure exerted by a gas is due to the average of the impulses exerted by the gas particles on the walls of the container. Most of the particles have speeds near the average speed, but some move very slowly and some very rapidly. The average speed is typically about 500 meters per second. The absolute temperature of a gas is proportional to the average kinetic energy of the gas particles.

The ideal gas law states the relationship between the pressure, the volume, the number of moles, and the absolute temperature of a gas as $PV = nRT$, where R is the gas constant.

CHAPTER 11 *Revisited*

Observation of the motion of smoke particles provided evidence of the existence of atoms and molecules. Knowledge of the volumes of gases that combined chemically to form other gases helped establish the masses of individual atoms and molecules. The ideal gas law tells us that the average kinetic energy of the gas particles is determined by the absolute temperature.

Key Terms

absolute temperature scale The temperature scale with its zero point at absolute zero and degrees equal to those on the Celsius scale. Also called the Kelvin temperature scale.

atom The smallest unit of an element that has the chemical and physical properties of that element.

atomic mass The mass of an atom in atomic mass units.

atomic mass unit One-twelfth of the mass of a carbon atom. One amu is equal to 1.66×10^{-27} kilogram.

Avogadro's number 6.02×10^{23} molecules, the number of molecules in 1 mole of any substance.

Celsius temperature scale The temperature scale with values of 0°C and 100°C for the temperatures of freezing and boiling water, respectively.

compound A combination of chemical elements that forms a substance with its own properties.

element Any chemical species that cannot be broken up into other chemical species.

Fahrenheit temperature scale The temperature scale with values of 32°F and 212°F for the temperatures of freezing and boiling water, respectively. Its degree is five-ninths of that on the Celsius or Kelvin scales.

ideal gas An enormous number of tiny particles separated by relatively large distances. The particles have no internal structure, are indestructible, and do not interact with each other except when they collide; all collisions are elastic.

ideal gas law $PV = nRT$, where P is the pressure, V is the volume, T is the absolute temperature, n is the number of moles, and R is the gas constant.

Kelvin temperature scale The temperature scale with its zero point at absolute zero and a degree equal to that on the Celsius scale. Also called the *absolute temperature scale*.

law of definite proportions When two or more elements combine to form a compound, the ratios of the masses of the combining elements have fixed values.

macroscopic Describes the bulk properties of a substance, such as mass, size, pressure, and temperature.

microscopic Describes properties not visible to the naked eye, such as atomic speeds or the masses and sizes of atoms.

mole The amount of a substance that has a mass in grams numerically equal to the mass of its molecules in atomic mass units.

molecule A combination of two or more atoms.

pressure The force per unit area of surface. Pressure is measured in newtons per square meter, or pascals.

Questions and exercises are paired so that most odd-numbered are followed by a similar even-numbered.
Blue-numbered questions and exercises are answered in Appendix B.
indicates more challenging questions and exercises.
WebAssign Many Conceptual Questions and Exercises for this chapter may be assigned online at WebAssign.

Conceptual Questions

1. The two essential elements of a good model are insight and predictive power. Many ancient cultures explained natural phenomena in terms of the actions of their gods. Did these models fail primarily because of lack of insight or lack of predictive power?
2. The two essential elements of a good model are insight and predictive power. Choose a model with which you are familiar and point out how it meets these two criteria.
3. A friend has created a model of how a candy vending machine works. His theory says that a little blue person (LBP) lives inside each vending machine. This person takes your coins and gives you candy in return. Although this LBP theory may not seem reasonable to you, can you suggest ways of disproving it without opening the machine?
4. For most of human history, we believed that Earth was stationary and the Sun and planets orbited Earth (the geocentric model). Beginning about 500 years ago, a second model emerged in which Earth orbits the Sun (the heliocentric model). When we read in the paper that the Sun rose at 6:40 this morning, which of these two models is being used?
5. Your friend notices that a brown can of diet cola floats, whereas a green can of lemon–lime soda and a can of orange soda both sink. He postulates a model in which only nonbrown cans of soda sink. To prove his model, he tries a brown can of diet root beer and finds that it floats as expected. Has he proven that his model is correct? In general, can a model ever be proven true?
6. Following the experiments described in Question 5, your friend tries a brown can of nondiet root beer and finds that it sinks. He rightfully discards his original model and proposes an alternative. What would this new model be? Has it been proven correct?
7. Alchemists held a model in which matter was continuous. Atomists showed the fallacy of this model and replaced it with a model in which all objects are made of small, discrete particles. In your day-to-day living, which model do you appeal to more often? Is the most complete model always the most useful?
8. What role did the alchemists play in the development of an atomistic world view?
9. Which of the following are not elements: hydrogen, salt, nitrogen, granite, sodium, chlorine, water?
10. Would you expect carbon monoxide to be an element or a compound? Why?
11. When the element mercury is heated in air, a red powder is formed. Careful measurement shows that the mass of the resulting powder is greater than the mass of the original mercury. Is this powder an element or a compound? How do you account for this additional mass?
12. Give an example that clearly illustrates the meaning of the law of definite proportions.
13. What are the basic differences between mixtures and compounds?
14. Do water and salt form a compound or a mixture?
15. The atomic mass of ammonia is 17 atomic mass units. What is the atomic mass of nitrogen if a molecule of ammonia consists of one atom of nitrogen and three atoms of hydrogen?
16. The atomic mass of iron oxide (rust) is 160 atomic mass units. What is the atomic mass of iron if a molecule of iron oxide consists of two atoms of iron and three atoms of oxygen?
17. Silver has an atomic mass of 108. Which, if either, contains more atoms: 1 gram of silver or 1 gram of hydrogen?
18. Silver has an atomic mass of 108. Which, if either, contains more atoms: 1 mole of silver or 1 mole of hydrogen?
19. How does the number of molecules in 1 liter of oxygen compare with the number of molecules in 1 liter of carbon dioxide if they are both at the same temperature and pressure?
20. Oxygen molecules contain two oxygen atoms, and carbon dioxide molecules contain one atom of carbon and two atoms of oxygen. How does the total number of atoms in 1 liter of oxygen compare with the total number of atoms in 1 liter of carbon dioxide if they are both at the same temperature and pressure?
21. The atomic mass of sulfur is 32 atomic mass units. How many grams of sulfur are needed to have an Avogadro's number of sulfur atoms?
22. How many grams of water are needed to have an Avogadro's number of water molecules?
23. If a gas condenses to a liquid, the liquid occupies a much smaller volume than the gas. How does the ideal gas model account for this?
24. The ideal gas model accounts very well for the behavior of gases at standard temperature and pressure. Would the ideal gas model begin to fail for very large pressures or for very small pressures? Explain your answer.

25. A cube and a spherical ball are made of the same material and have the same mass. Which exerts the larger pressure while resting on a floor?

26. You can apply enough force to the head of a pushpin to push it into a plaster wall with your thumb. However, it is not a good idea to try to do this with a needle. Use the concept of pressure to explain the difference between these two situations.

© Cengage Learning/George Semple

27. If you screw the cap of an empty plastic drinking bottle on tightly while walking in the mountains, why are the sides of the bottle caved in when you return to the valley?

28. Your right rear tire has to support a weight of 3000 newtons. Normally, the contact area of your tire with the road is 200 square centimeters. If the pressure in your tire is suddenly reduced from 32 pounds per square inch to 16 pounds per square inch, what must be the new contact area to support the car?

29. Use the microscopic model of a gas to explain why the pressure in a tire increases as you add more air.

30. As you drive your car down the road, the friction of the rubber with the road causes the air inside the tire to increase in temperature, resulting in an increase in pressure. Use the microscopic model of a gas to explain why the pressure increases.

31. If the average speed of a perfume molecule is 500 meters per second, why does it take several minutes before you smell the perfume from a bottle opened across the room?

32. What happens to the average speed of the molecules of a gas as it is heated?

33. Why does an alcohol-in-glass thermometer have a bulb at the bottom?

34. It is possible to cut the very top off an alcohol-in-glass thermometer without any of the alcohol spilling out. However, it will no longer function as a good thermometer. Why not?

35. It takes longer to boil an egg in the mountains than it does at sea level. What conditions must be imposed before the boiling point of water can be used as a fixed temperature?

36. Why is body temperature not a good fixed temperature for establishing a temperature scale?

37. Two students are sick in bed with 2-degree fevers. One has a temperature of 39.0°C; the other, 100.6°F. Which student has the higher fever?

38. Is a sauna at a temperature of 190°F hotter or colder than one at 90°C?

39. At what temperature should you set your new Celsius thermostat so that your hot tub stays at a comfortable 102°F?

© Image Source/Jupiterimages

40. You move to Canada and find that the thermostat in your home is in Celsius degrees. You normally like your house at about 72°F. To what temperature should you set your new thermostat?

41. What is the freezing point of water on the Kelvin scale?

42. Nitrogen boils at 77 K. At what Celsius temperature does it boil?

43. What microscopic property of an ideal gas doubles when the absolute temperature is doubled?

44. What temperature change would be needed to double the average speed of the molecules in an ideal gas?

45. Air is a mixture of several gases, primarily nitrogen and oxygen. Is the average kinetic energy of the nitrogen molecules greater than, equal to, or less than the average kinetic energy of the oxygen molecules?

46. Consider a mixture of helium and neon gases. The atomic masses of helium and neon are 4 atomic mass units and 20 atomic mass units, respectively. Is the average speed of a helium atom greater than, equal to, or less than the average speed of a neon atom?

47. If you heat a gas in a container with a fixed volume, the pressure increases. Use the ideal gas model to explain this.

48. If the volume of an ideal gas is held constant, what happens to the pressure if the absolute temperature is cut in half?

49. What macroscopic property of an ideal gas doubles when the absolute temperature is doubled while the pressure remains constant?
50. If you put a sealed plastic bottle partially filled with hot tea in the refrigerator, the sides of the bottle will cave in as the tea cools. Why?
51. What happens to the temperature of an ideal gas if you reduce its volume to one-fourth while holding the pressure constant?
52. Why does the pressure inside the tires increase after a car has been driven?
53. Use the microscopic gas model to explain why the pressure of a gas rises as the volume is reduced while the temperature remains constant.
54. If you hold the temperature of an ideal gas constant, what happens to its volume when you triple its pressure?
55. The water in a canvas water bag placed in front of your car when driving across the desert stays cooler than the surrounding air. Explain this in terms of the average kinetic energies of the water molecules that leave and those that stay behind.

Gerald F. Wheeler

56. How does an alcohol rub cool your body?

Exercises

57. If 1 g of hydrogen combines completely with 8 g of oxygen to form water, how many grams of hydrogen are needed to combine completely with 24 g of oxygen?
58. In ammonia, 14 g of nitrogen combines completely with 3 g of hydrogen. How many grams of hydrogen are needed to combine completely with 56 g of nitrogen?
59. Given that 1 g of hydrogen combines completely with 8 g of oxygen to form water, how many grams of water can you make with 8 g of hydrogen and 16 g of oxygen?
60. Given that 12 g of carbon combines completely with 16 g of oxygen to form carbon monoxide, how many grams of carbon monoxide can be made from 48 g of carbon and 48 g of oxygen?
61. A ham sandwich consists of one slice of ham (10 g) and two slices of bread (25 g each). You have 1 kg of ham and 1 kg of bread. You make as many sandwiches as you can. How many sandwiches did you make? What is the mass of the sandwiches? Which ingredient is left over? What is the mass of the ingredient that is left over?
62. One mole of water molecules consists of 1 mole of oxygen (16 g) and 2 moles of hydrogen (1 g each). You combine 1 kg of oxygen with 1 kg of hydrogen to make water. How many moles of water did you make? What is the mass of the water? What is the mass of the element that is left over?
63. Given that the carbon atom has a mass of 12 amu, how many carbon atoms are there in a diamond with a mass of 1 g?
64. Given that the sulfur molecule has a mass of 32 amu, how many sulfur molecules are in 1 g of sulfur?
65. One liter of water has a mass of 1 kg, and the mass of a water molecule is 18 amu. How many molecules of water are in 1 L of water?
66. One liter of oxygen has a mass of 1.4 g, and the oxygen molecule has a mass of 32 amu. How many oxygen molecules are in 1 L of oxygen?
67. One liter of nitrogen combines with 3 L of hydrogen to form 2 L of ammonia. If the molecules of nitrogen and hydrogen have two atoms each, how many atoms of hydrogen and nitrogen are in one molecule of ammonia?
68. One liter of oxygen combines with 1 L of hydrogen to form 1 L of hydrogen peroxide. Given that the molecules of hydrogen and oxygen contain two atoms each, how many atoms are in one molecule of hydrogen peroxide?
69. About how many atoms would it take to deposit a single layer on a surface with an area of 1 cm^2?
70. About how many atoms would you expect there to be in a cube of material 1 cm on each side?
71. You exert a force of 30 N on the head of a thumbtack. The head of the thumbtack has a radius of 5 mm. What is the pressure on your thumb?
72. The pressure in each of your car tires is 2.5×10^5 Pa. The mass of your car is 1600 kg. Assuming that each of your tires bears one-quarter of the total load, what is the contact area of each tire with the road?

73. What happens to the volume of 1 L of an ideal gas when the pressure is tripled while the temperature is held fixed?

74. An ideal gas at 27°C is contained in a piston that ensures that its pressure will always be constant. Raising the temperature of the gas causes it to expand. At what temperature will the gas take up twice its original volume?

75. A helium bottle with a pressure of 100 atm has a volume of 3 L. How many balloons can the bottle fill if each balloon has a volume of 1 L and a pressure of 1.25 atm?

76. When the temperature of an automobile tire is 20°C, the pressure in the tire reads 32 psi on a tire gauge. (The gauge measures the difference between the pressures inside and outside the tire.) What is the pressure when the tire heats up to 40°C while driving? You may assume that the volume of the tire remains the same and that atmospheric pressure is a steady 14 psi.

77. A volume of 150 cm^3 of an ideal gas has an initial temperature of 20°C and an initial pressure of 1 atm. What is the final pressure if the volume is reduced to 100 cm^3 and the temperature is raised to 40°C?

78. An ideal gas has the following initial conditions: V_i = 500 cm^3, P_i = 3 atm, and T_i = 100°C. What is its final temperature if the pressure is reduced to 1 atm and the volume expands to 1000 cm^3?

12

States of Matter

▶Many materials exist as solids, liquids, or gases, each with its own characteristics. However, different materials share many characteristics; for instance, many materials form crystalline shapes in the solid form. **What does the shape of a crystal tell us about the underlying structure of the material?**

(See page 255 for the answer to this question.)

Ice crystals

ALL matter is composed of approximately 100 different elements. Yet the material world we experience—say, in a walk through the woods—holds a seemingly endless variety of forms. This variety arises from the particular combinations of elements and the structures they form, which can be divided into four basic forms, or states: solid, liquid, gas, and plasma.

Many materials can exist in the solid, liquid, and gaseous states if the forces holding the chemical elements together are strong enough that their melting and vaporization temperatures are lower than their decomposition temperatures. Hydrogen and oxygen in water, for example, are so tightly bonded that water exists in all three states. Sugar, on the other hand, decomposes into its constituent parts before it can turn into a gas.

If we continuously heat a solid, the average kinetic energy of its molecules rises and the temperature of the solid increases. Eventually, the intermolecular bonds break, and the molecules slide over one another (the process called melting) to form a liquid. The next change of state occurs when the substance turns into a gas. In the gaseous state, the molecules have enough kinetic energy to be essentially independent of each other. In a plasma, individual atoms are ripped apart into charged ions and electrons, and the subsequent electrical interactions drastically change the resulting substance's behavior.

Atoms

At the end of the previous chapter, we established the evidence for the existence of atoms. It would be natural to ask, "Why stop there?" Maybe atoms are not the end of our search for the fundamental building blocks of matter. In fact, they are not. Atoms have structure, and we will devote two chapters near the end of the book to further developing our understanding of this structure. For now it is useful to know a little about this structure so that we can understand the properties of the states of matter.

A useful model for the structure of an atom for our current purposes is the solar- system model developed early in the 20th century. In this model the atom is seen as consisting of a tiny central nucleus that contains almost all of the atom's mass. This nucleus has a positive electric charge that binds very light, negatively charged electrons to the atom in a way analogous to the Sun's gravitational attraction for the planets. The electrons' orbits define the size of the atom and give it its chemical properties.

The basic force that binds materials together is the electrical attraction between atomic and subatomic particles. As we will see in later chapters, the gravitational force is too weak and the nuclear forces are too short-ranged to have much effect in chemical reactions. We live in an electrical universe when it comes to the states of matter. How these materials form depends on these electric forces. And the form they take determines the properties of the materials.

Density

Extended presentation available in the *Problem Solving* supplement

One characteristic property of matter is its **density.** Unlike mass and volume, which vary from one object to another, density is an inherent property of the material. A ton of copper and a copper coin have drastically different masses and volumes but identical densities. If you were to find an unknown material and could be assured that it was pure, you could go a long way toward identifying it by measuring its density.

Density is defined as the amount of mass in a standard unit of volume and is expressed in units of kilograms per cubic meter (kg/m^3):

density $= \dfrac{\text{mass}}{\text{volume}}$

$$D = \frac{M}{V}$$

For example, an aluminum ingot is 3 meters long, 1 meter wide, and 0.3 meter thick. If it has a mass of 2430 kilograms, what is the density of aluminum? We calculate the volume first and then the density:

$$V = lwh = (3\text{ m})(1\text{ m})(0.3\text{ m}) = 0.9\text{ m}^3$$

$$D = \frac{M}{V} = \frac{2430\text{ kg}}{0.9\text{ m}^3} = 2700\text{ kg/m}^3$$

Therefore, the density of aluminum is 2700 kilograms per cubic meter. Densities are also often expressed in grams per cubic centimeter. Thus, the density of aluminum is also 2.7 grams per cubic centimeter (g/cm^3). Table 12-1 gives the densities of a number of common materials.

Q: Which has the greater density, 1 kilogram of iron or 2 kilograms of iron?

A: They have the same density; the density of a material does not depend on the amount of material.

Q: If a hollow sphere and a solid sphere are both made of the same amount of iron, which sphere has the greater average density?

A: The solid sphere has the greater average density because it occupies the smaller volume for a given mass of iron.

Table 12-1 *Densities of Some Common Materials*

Material	Density (g/cm³)
Air*	0.0013
Ice	0.92
Water	1.00
Magnesium	1.75
Aluminum	2.70
Iron	7.86
Copper	8.93
Silver	10.5
Lead	11.3
Mercury	13.6
Uranium	18.7
Gold	19.3
Osmium	22.5

*At 0°C and 1 atm.

The densities of materials range from the small for a gas under normal conditions to the large for the element osmium. One cubic meter of osmium has a mass of 22,480 kilograms (a weight of nearly 50,000 pounds), about 22 times as large as the same volume of water. It is interesting to note that the osmium atom is less massive than a gold atom. Therefore, the higher density of osmium indicates that the osmium atoms must be packed closer together.

The materials that we commonly encounter have densities around the density of water, 1 gram per cubic centimeter. A cubic centimeter is about the volume of a sugar cube. The densities of surface materials on Earth average approximately 2.5 grams per cubic centimeter. The density at Earth's core is about 9 grams per cubic centimeter, making Earth's average density about 5.5 grams per cubic centimeter.

Solids

Solids have the greatest variety of properties of the four states of matter. The character of a solid substance is determined by its elemental constituents and its particular structure. This underlying structure depends on the way it was formed. For example, slow cooling often leads to solidification with the atoms in an ordered state known as a **crystal.**

Crystals grow in a variety of shapes. Their common property is the orderliness of their atomic arrangements. The orderliness consists of a basic arrangement of atoms that repeats throughout the crystal, analogous to the repeating geometric patterns in some wallpapers.

The microscopic order of the atoms is not always obvious in macroscopic samples. For one thing, few perfect crystals exist; most samples are aggregates

Everyday Physics | *Density Extremes*

Which weighs more: a pound of feathers or a pound of iron? The answer to this junior high school puzzle, of course, is that they weigh the same. The key difference between the two materials is *density*; although the two weigh the same, they have very different volumes. Density is a comparison of the masses of two substances with the same volumes. Obviously, 1 cubic meter of iron has much more mass than 1 cubic meter of feathers.

The densities of objects vary over a large range. The densities of common Earth materials pale in comparison to those of some astronomical objects. After a star runs out of fuel, its own gravitational attraction causes it to collapse. The collapse stops when the outward forces due to the pressure in the star balance the gravitational forces. The resultant stellar cores can have astronomically large densities. White dwarf stars are the death stage of most stars. They can have masses up to 1.4 times that of our Sun compressed to a size about that of Earth, with resulting densities a million times the density of water. Neutron stars are cores left after a star explodes and can have densities a billion times those of white dwarfs. A teaspoon of material from a neutron star would weigh a billion tons on Earth!

A very low-density solid, called *silica aerogel,* was created at the Lawrence Livermore National Laboratory in California. This solid is made from silicon dioxide and has a density that is only three times that of air. Because of this very low density, it is sometimes known as "solid smoke." Because silica aerogel is a solid, it holds its shape. In fact, it can support 1600 times its own weight!

Silica aerogel has an extremely low density but still can support 1600 times its own weight.

The density of interstellar space is much smaller than that of air; there is about one atom per cubic centimeter, resulting in a density about one-billion-trillionth that of air at 1 atmosphere of pressure, or about one-trillion-trillionth (10^{-24}) that of water.

WORKING IT OUT | *Density*

Suppose you find a chunk of material that you cannot identify. You find that the chunk has a mass of 87.5 g and a volume of 50 cm^3. What is the material, and what is the mass of a 6-cm^3 piece of this material?

We could easily find the mass of 6 cm^3, if only we knew the mass of 1 cm^3. This is just the density. We can find the density from the measurements made on the original chunk:

$$D = \frac{M}{V} = \frac{87.5\ \text{g}}{50\ \text{cm}^3} = 1.75\ \text{g/cm}^3$$

This density is the same as that of magnesium. Therefore, the material could be magnesium, but we would need to look at other characteristics to be sure.

The 6-cm^3 piece has a mass six times as large as the mass of 1 cm^3:

$$M = DV = (1.75\ \text{g/cm}^3)(6\ \text{cm}^3) = 10.5\ \text{g}$$

of small crystals. However, macroscopic evidence of this underlying structure does exist. A common example in northern climates is a snowflake (Figure 12-1). Its sixfold symmetry is evidence of the structure of ice. Another example is mica (Figure 12-2), a mineral you may find on a hike in the woods. Shining flakes of mica can be seen in many rocks. Larger pieces can be easily separated into thin sheets. The thinness of the sheets seems (at least on the macroscopic

Figure 12-1 The sixfold symmetry exhibited by snowflakes is evidence that ice crystals have hexagonal shapes.

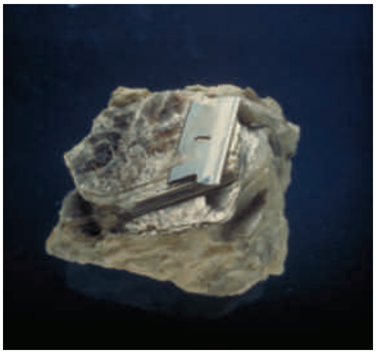


Figure 12-2 Samples of mica exhibit a two-dimensional crystalline structure as evidenced by the fact that one can peel thin sheets from the larger crystal.

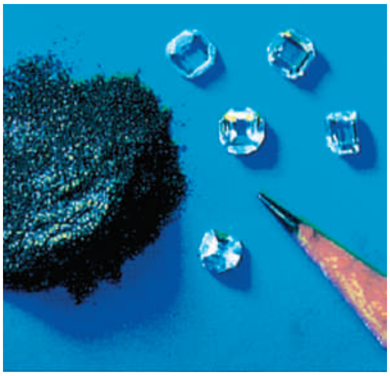


Figure 12-3 Synthetic diamonds and finely divided graphite are two different crystalline forms of carbon.

Figure 12-4 A glass filled with milk beyond the brim is evidence of surface tension.

scale) to be limitless. It is easy to convince yourself that the atoms in mica are arranged in two-dimensional sheets with relatively strong bonds between atoms within the sheet and much weaker bonds between the sheets.

In contrast to mica, ordinary table salt exhibits a three-dimensional structure of sodium and chlorine atoms. If you dissolve salt in water and let the water slowly evaporate, the salt crystals that form have obvious cubic structures. If you try to cut a small piece of salt with a razor blade, you find that it doesn't separate into sheets like mica but fractures along planes parallel to its faces. (Salt from a saltshaker displays this same structure, but the grains are usually much smaller. A simple magnifying glass allows you to see the cubic structure.) Precious stones also have planes in their crystalline structure. A gem cutter studies the raw gemstones carefully before making the cleavages that produce a fine piece of jewelry.

Some substances have more than one crystalline structure. A common example is pure carbon. Carbon can form diamond or graphite crystals (Figure 12-3). Diamond is a very hard substance that is treasured for its optical brilliance. Diamond has a three-dimensional structure. Graphite, on the other hand, has a two-dimensional structure like that of mica, creating sheets of material that are relatively free to move over each other. Because of its slippery nature, graphite is used as a lubricant and as the "lead" in pencils.

Liquids

When a solid melts, interatomic bonds break, allowing the atoms or molecules to slide over each other, producing a **liquid.** Liquids fill the shape of the container that holds them, much like the random stacking of a bunch of marbles.

The temperature at which a solid melts varies from material to material simply because the bonding forces are different. Hydrogen is so loosely bound that it becomes a liquid at 14 K. Oxygen and nitrogen—the constituents of the air we breathe—melt at 55 K and 63 K, respectively. The fact that ice doesn't melt until 273 K (0°C) tells us that the bonds between the molecules are relatively strong.

Water is an unusual liquid. Although water is abundant, it is one of only a few liquids that occur at ordinary temperatures on Earth. The bonding between the water molecules is relatively strong, and a high temperature is required to separate them into the gaseous state.

The intermolecular forces in a liquid create a special "skin" on the surface of the liquid. This can be seen in Figure 12-4, in which a glass has been filled with milk beyond its brim. What is keeping the extra liquid from flowing over the edge?

Everyday Physics | *Solid Liquids and Liquid Solids*

Many substances exist between the ordinary boundaries of solids and liquids. When materials such as glass or wax cool, the molecules are frozen in space without arranging themselves into an orderly crystalline structure. These solids are *amorphous*, meaning that they retain some of the properties of liquids. A common example of an amorphous solid is a clear lollipop made by rapidly cooling liquid sugar. The average intermolecular forces in an amorphous material are weaker than those in a crystalline structure.

Despite the solid rigidity of an amorphous material, this form is more like a liquid than a solid because of its lack of order. In addition, the melting points of amorphous materials are not clearly defined. An amorphous material simply gets softer and softer, passing into the fluid state. Another characteristic of these solid liquids is that they actually do flow like a liquid, although many flow on time scales that make the flow difficult or impossible to detect. Although it is widely believed that old church windows in Europe are thicker at the bottom than at the top because of centuries of flow, they were most likely assembled with the thicker edges at the bottom.

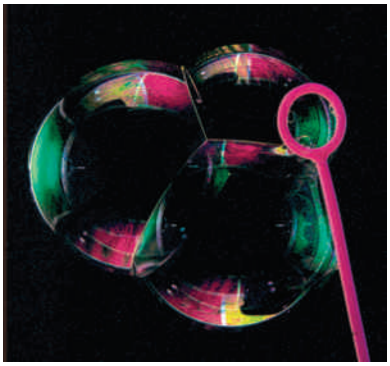
Other substances are liquids that retain some degree of orderliness, characteristic of solids. Liquid crystals can be poured like regular liquids. They lack positional order, but they possess an orientational order. Small electric fields can align the rodlike molecules along a particular direction.

Liquid crystals have some interesting applications because polarized light behaves differently depending on whether it is traveling parallel or perpendicular to the alignment direction. For example, the orientation can be manipulated electrically to produce the numbers in a digital watch or an electronic calculator. You can verify that the light emerging from a liquid crystal display is polarized by looking at the display through polarized sunglasses. Changing the orientation of the sunglasses will vary the intensity of the image.

1. What properties of liquids are shared by amorphous materials?
2. What characteristic of solids is exhibited by liquid crystals?

© Courtesy of Sharp

The display on this LCD TV is an application of liquid crystal technology.



Aaron Haupt/Photo Researchers, Inc.

Figure 12-5 Surface tension minimizes the surface area of the soap film forming these bubbles.

Imagine two molecules, one on the surface of a liquid and one deeper into the liquid. The molecule beneath the surface experiences attractive forces in all directions because of its neighbors. The molecule on the surface only feels forces from below and to the sides. This imbalance tends to pull the "surface" molecules back into the liquid.

Surface tension also tries to pull liquids into shapes with the smallest possible surface areas. The shapes of soap bubbles are determined by the surface tension trying to minimize the surface area of the film (Figure 12-5). If there are no external forces, the liquid forms into spherical drops. In fact, letting liquids cool in space has been proposed as a way of making nearly perfect spheres. In the free-fall environment of an orbiting space shuttle, liquid drops are nearly spherical.

Surface tensions vary among liquids. Water, as you may expect, has a relatively high surface tension. If we add soap or oil to the water, its surface tension is reduced, meaning that the water molecules are not as attracted to each other. It is probably reasonable to infer that the new molecules in the solution are somehow shielding the water molecules from each other.

Gases

When the molecules separate totally, a liquid turns into a **gas.** (See Chapter 11 for a discussion of an ideal gas.) The gas occupies a volume about 1000 times as large as that of the liquid. In the gaseous state, the molecules have enough kinetic energy to be essentially independent of each other. A gas fills the container holding it, taking its shape and volume. Because gases are mostly empty space, they are compressible and can be readily mixed with each other.

Gases and liquids have some common properties because they are both "fluids." All fluids are able to flow, some more easily than others. The **viscosity** of a fluid is a measure of the internal friction within the fluid. You can get a qualitative feeling for the viscosity of a fluid by pouring it. Fluids that pour easily, such as water and gasoline, have low viscosities. Those that pour slowly, such as molasses, honey, and egg whites, have high viscosities. Glass is a fluid with an extremely high viscosity. In the winter, drivers put lower-viscosity oils in their cars so that the oils will flow better on cold mornings.

The viscosity of a fluid determines its resistance to objects moving through it. A parachutist's safe descent is due to the viscosity of air. Air and water have drastically different viscosities. Imagine running a 100-meter dash in water 1 meter deep!

© Cengage Learning/Charles D. Winters

Honey is a very viscous fluid.

Q: How might you explain the observation that the viscosities of fluids decrease as they are heated?

A: The increased kinetic energy of the molecules means that the molecules are more independent of each other.

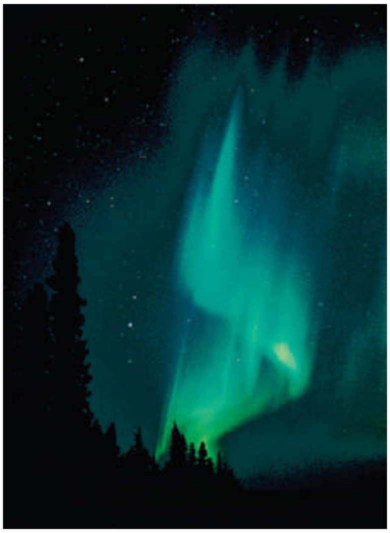
Plasmas

At around 4500°C, all solids have melted. At 6000°C, all liquids have been turned into gases. And at somewhere above 100,000°C, most matter is ionized into the **plasma** state. In the transition between a gas and a plasma, the atoms break apart into electrically charged particles.

Although the fourth state of matter, plasma, is more rare on Earth than the solid, liquid, and gaseous states, it is actually the most common state of matter in the universe (more than 99%). Examples of naturally occurring plasmas on Earth include fluorescent lights and neon-type signs. Fluorescent lights consist of a plasma created by a high voltage that strips mercury vapor of some of its electrons. "Neon" signs employ the same mechanism but use a variety of gases to create the different colors.

Perhaps the most beautiful naturally occurring plasma effect is the aurora borealis, or northern lights. Charged particles emitted by the Sun and other stars are trapped in Earth's upper atmosphere to form a plasma known as the Van Allen radiation belts. These plasma particles can interact with atoms of nitrogen and oxygen over both magnetic poles, causing them to emit light as discussed in Chapter 23.

Plasmas are important in nuclear power as well as in the interiors of stars. An important potential energy source for the future is the "burning" of a plasma of hydrogen ions at extremely high temperatures to create nuclear energy. We will discuss nuclear energy more completely in Chapter 26.


Jack Finch/SPL/Photo Researchers, Inc.

The aurora borealis results from the interaction of charged particles with air molecules.

Pressure

A characteristic feature of a fluid—either a gas or a liquid—is its change in pressure with depth. As we saw in Chapter 11, pressure is the force per unit area exerted on a surface, measured in units of newtons per square meter (N/m^2), a unit known as a pascal (Pa).

When a gas or liquid is under the influence of gravity, the weight of the material above a certain point exerts a force downward, creating the pressure at that point. Therefore, the pressure in a fluid varies with depth. You have probably felt this while swimming. As you go deeper, the pressure on your eardrums increases. If you swim horizontally at this depth, you notice that the pressure doesn't change. In fact, there is no change if you rotate your head; the pressure at a given depth in a fluid is the same in all directions.


© Photodisc Green/Getty Images

The pressure on a scuba diver increases with depth.

Consider the box of fluid shown in Figure 12-6. Because the fluid in the box does not move, the net force on the fluid must be zero. Therefore, the fluid below the box must be exerting an upward force on the bottom of the box that is equal to the weight of the fluid in the box plus the force of the atmosphere on the top of the box. The pressure at the bottom of the box is just this force per unit area.

Our atmosphere is held in a rather strange container: Earth's two-dimensional surface. Gravity holds the atmosphere down so that it doesn't escape. There is no definite top to our atmosphere; it just gets thinner and thinner the higher you go above Earth's surface.

The air pressure at Earth's surface is due to the weight of the column of air above the surface. At sea level the average atmospheric pressure is about 101 kilopascals. This means that a column of air that is 1 square meter in cross section and reaches to the top of the atmosphere weighs 101,000 newtons and has a mass of 10 metric tons. A column of air 1 square inch in cross section weighs 14.7 pounds; therefore, atmospheric pressure is also 14.7 pounds per square inch.

We can use these ideas to describe what happens to atmospheric pressure as we go higher and higher. You may think that the pressure drops to one-half the surface value halfway to the "top" of the atmosphere. However, this is not true, because the air near Earth's surface is much denser than that near the top of the atmosphere. This means that there is much less air in the top half compared to the bottom half. Because the pressure at a given altitude depends on the weight of the air above that altitude, the pressure changes more quickly near the surface. In fact, the pressure drops to half at about 5500 meters (18,000 feet) and then drops by half again in the next 5500 meters.

Are You On the Bus?

Q: Why doesn't the large force on the surface of your body crush you?

A: You aren't crushed because the pressure inside your body is the same as the pressure outside. Therefore, the inward force is balanced by the outward force.

Figure 12-6 The force on the bottom of the box of fluid is equal to the weight of the fluid in the box plus the force of the atmosphere on the top of the box.

This means that commercial airplanes flying at a typical altitude of 36,000 feet experience pressures that are only one-fourth those at the surface.

Like fish living on the ocean floor, we land-lovers are generally unaware of the pressure due to the ocean of air above us. Although the atmospheric pressure at sea level may not seem like much, consider the total force on the surface of your body. A typical human body has approximately 2 square meters (3000 square inches) of surface area. This means that the total force on the body is about 200,000 newtons (20 tons!).

An ingenious experiment conducted by a contemporary of Isaac Newton demonstrated the large forces that can be produced by atmospheric pressure. German scientist Otto von Guericke joined two half spheres (Figure 12-7) with just a simple gasket (no clamps or bolts). He then pumped the air from the sphere, creating a partial vacuum. Two teams of eight horses could not pull the hemispheres apart!

In weather reports, atmospheric pressure is often given in units of millimeters or inches of mercury. A typical pressure is 760 millimeters (30 inches) of mercury. Because pressure is a force per unit area, reporting pressure in units of length must seem strange. This scale comes from the historical method of measuring pressure. Early pressure gauges were similar to the simple mercury barometer shown in Figure 12-8. A sealed glass tube is filled with mercury and inverted into a bowl of mercury. After inversion the column of mercury does not pour out into the bowl but maintains a definite height above the pool of mercury. Because the mercury is not flowing, we know that the force due to atmospheric pressure at the bottom of the column is equal to the weight of the mercury column. This means that the atmospheric pressure is the same as the pressure at the bottom of a column of mercury 760 millimeters tall if there is a vacuum above the mercury. Therefore, atmospheric pressure can be characterized by the height of the column of mercury it will support.

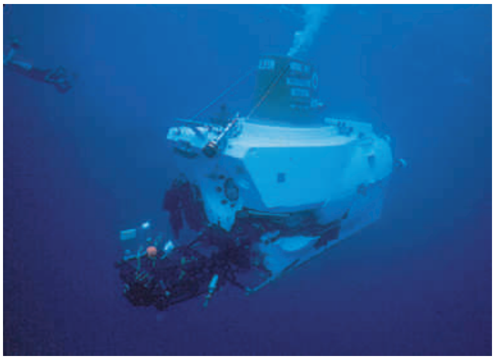
Atmospheric pressure also allows you to drink through a straw. As you suck on the straw, you reduce the pressure above the liquid in the straw, allowing the pressure below to push the liquid up. In fact, if you could suck hard enough to produce a perfect vacuum above water, you could use a straw 10 meters (almost 34 feet) long! So although we often talk of sucking on a soda straw and pulling the soda up, in reality we are removing the air pressure on the top of the soda column in the straw, and the atmospheric pressure is pushing the soda up.

Are You On the Bus?

Q: How high a straw could you use to suck soda?

A: Because soda is mostly water, we assume that it has the same density as water. Therefore, the straw could be 10 meters high—but only if you have very strong lungs. A typical height is more like 5 meters.

Figure 12-7 Two teams of eight horses could not separate von Guericke's evacuated half spheres.



Rod Catanach, Woods Hole Oceanographic Institution

Underwater explorers must use vessels such as this bathysphere at the great depths of the ocean floor.

Figure 12-8 In a mercury barometer, the atmospheric pressure is balanced by the pressure due to the weight of the mercury column.

As you dive deeper in water, the pressure increases for the same reasons as in air. Because atmospheric pressure can support a column of water 10 meters high, we have a way of equating the two pressures. The pressure in water must increase by the equivalent of 1 atmosphere (atm) for each 10 meters of depth. Therefore, at a depth of 10 meters, you would experience a pressure of 2 atmospheres, 1 from the air and 1 from the water. The pressures are so large at great depths that very strong vessels must be used to prevent the occupants from being crushed.

Q: What is the pressure on a scuba diver at a depth of 30 meters (100 feet)?

A: The pressure would be (30 meters)/(10 meters per atmosphere) = 3 atmospheres because of the water plus 1 atmosphere because of the air above the water, for a total of 4 atmospheres.

FLAWED REASONING

Jeff designs a new scuba setup that is so profoundly simple he is surprised that no one has thought of this before. He has attached one end of a long garden hose to a large block of Styrofoam to keep the hose above the water level. He will breathe through the other end of the hose as he explores the depths. **What is wrong with Jeff's simple design?**

ANSWER If Jeff dives 10 meters below the surface, the water will push inward on him with 2 atmospheres of pressure. Therefore, the air in his lungs will be at a pressure of 2 atmospheres. Because the air in the hose will be at a pressure of 1 atmosphere, air will be expelled from his lungs and he will not be able to breathe!

Sink and Float

Floating is so commonplace to anyone who has gone swimming that it may not have occurred to you to ask, "Why do things sink or float?" "Why does a golf ball sink and an ocean liner float?" "How is a hot-air balloon similar to an ocean liner?"

Anything that floats must have an upward force counteracting the force of gravity, because we know from Newton's first law of motion (Chapter 3) that an object at rest has no unbalanced forces acting on it. To understand why things float therefore requires that we find the upward buoyant force opposing the gravitational force.

The buoyant force exists because the pressure in the fluid varies with depth. To understand this, consider the cubic meter of fluid in Figure 12-9. The pressure on the bottom surface is greater than on the top surface, resulting in a net upward force. The downward force on the top surface is due to the weight of the fluid above the cube. The upward force on the bottom surface is equal to the weight of the column of fluid above the bottom of the cube. The difference between these two forces is just the weight of the fluid in the cube. Therefore, the net upward force must be equal to the weight of the fluid in the cube.

These pressures do not change if a cube of some other material replaces the cube of fluid. Therefore, the net upward force is still equal to the weight of the fluid that was replaced. This result is known as **Archimedes' principle,** named for the Greek scientist who discovered it.

Archimedes' principle ▶

The buoyant force is equal to the weight of the displaced fluid.

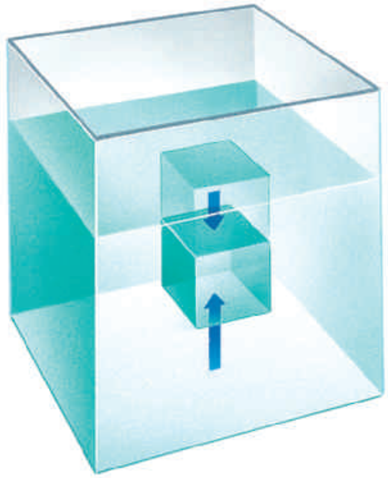


Figure 12-9 The buoyancy force on the cube is due to the larger pressure on the lower surface.

When you lower an object into a fluid, it displaces more and more fluid as it sinks lower into the liquid, and the buoyant force therefore increases. If the buoyant force equals the object's weight before it is fully submerged, the object floats. This occurs whenever the density of the object is less than that of the fluid.

We can change a "sinker" into a "floater" by increasing the amount of fluid it displaces. A solid chunk of steel equal in weight to an ocean liner clearly sinks in water. We can make the steel float by reshaping it into a hollow box. We don't throw away any material; we only change its volume. If we make the volume big enough, it will displace enough water to float.

WORKING IT OUT *Buoyant Force*

A piece of iron with a mass of 790 grams displaces 100 grams of water when it is submerged. If we lower the piece of iron under the surface of a lake and then release it from rest, what will its initial acceleration be as it sinks to the bottom of the lake?

The free-body diagram for the piece of iron will initially have two forces, the gravitational force (true weight) and the buoyant force, as shown in Figure 12-10. (After the iron begins moving, there will also be a drag force, but we are calculating the initial acceleration, right after release.) The gravitational force is given by $mg = (0.79$ kilogram)[10 (meters per second) per second] $= 7.9$ newtons. The buoyant force will be equal to the weight of the water that is displaced by the piece of iron. The volume of the water displaced will be equal to the volume of the iron, 100 cm^3, and this much water will have a mass of 100 g $= 0.1$ kg. The buoyant force is equal to the weight of 0.1 kg of water, or 1 newton. The acceleration is caused by the net force, which is 7.9 newtons $-$ 1.0 newton $=$ 6.9 newtons. Newton's second law yields an acceleration of

$$a = \frac{F_{net}}{m} = \frac{6.9 \text{ N}}{0.79 \text{ kg}} = 8.7 \text{ m/s}^2$$

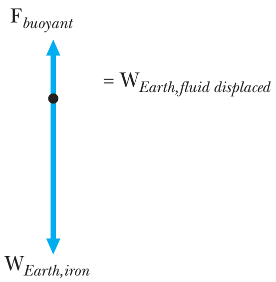


Figure 12-10 Free-body diagram for the piece of iron right after it is released under the surface of the lake.

T. Nakamura/Superstock, Inc.

Changing the shape of the steel makes it a "floater." A solid piece of steel with the mass of the ocean liner sinks.

Everyday Physics | *How Fatty Are You?*

Exercising does not automatically reduce your weight. One outcome of exercising is the conversion of fatty tissue into muscle without changing your weight. Because healthy people have more muscle, it is important to be able to determine the percentage of body fat. That's a question that just stepping on the bathroom scale won't tell you. However, a 2000-year-old technique developed by Archimedes does work.

Around 250 BC, Archimedes was chief scientist for King Hiero of Syracuse (now modern Sicily). As the story goes, the king was concerned that his crown was not made of pure gold but had some silver hidden under its surface. Not wanting to destroy his crown to find out whether he had been cheated, he challenged his scientist to find an alternative procedure. Everybody knows the legend of Archimedes leaping from his bathtub and shouting, "Eureka, I have found it!"

The key to Archimedes' solution is determining the average density of the crown or, in our case, your body. There is no problem getting your weight. A simple bathroom scale will do. The tricky part is determining your volume. You, like the king's crown, are oddly shaped (sorry!), not matching any of the geometric volumes you studied in school.

Archimedes discovered that an object immersed in water feels an upward buoyant force. If you were to stand on a scale while totally submerged, the reading on the scale (your apparent weight) would be less than your true weight because the buoyant force supports part of your weight. This buoyant force is equal to the weight of the water your body displaces. From your measured weights in air and under water, your volume can be calculated.

Human performance scientists consider the body to be made of fat and "muscle." (Everything but fat—skin, bone, and organs—is grouped as muscle.) From the study of cadavers, the density of human fat is found to be about 90% the density of water, whereas the density of "muscle" is about 110% the density of water. The more fat you have, the lower your average density will be. The percentage of fat for healthy adults should be between 15% and 20% for men and between 22% and 28% for women. Champion distance runners and bicyclists have about 5–8% fat.


© Taxi/Getty Images

1. If your percentage of body fat is 20%, do you float or sink in a pond of fresh water?
2. Your friend claims that she weighs less when she is submerged in water. You understand what she means, but her physics is not correct. Use the concept of apparent weight as you explain the error in your friend's comment.

Ice floats because of a **buoyant force.** When water freezes, the atoms arrange themselves in a way that actually takes up more volume. As a result, ice has a lower density than liquid water and floats on the surface. This is fortunate; otherwise, ice would sink to the bottom of lakes and rivers, freezing the fish and plants.

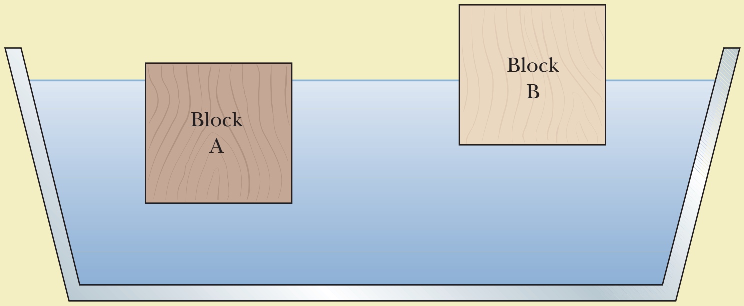
The buoyant force is present even when the object sinks! For example, any object appears to weigh less in water than in air. You can verify this by hanging a small object by a rubber band. As you lower it into a glass of water, the rubber band is stretched less because the buoyant force helps support the object.

Bernoulli's Effect

The pressure in a stationary fluid changes with depth but is the same if you move horizontally. If the fluid is moving, however, the pressure can also change in the horizontal direction. Suppose we have a pipe that has a narrow section

FLAWED REASONING

Two wooden blocks with the same size and shape are floating in a bucket of water. Block A floats low in the water, and block B floats high, as shown in the following figure.



Three students have just come from an interesting lecture on Archimedes' principle and are discussing the buoyant forces on the blocks.

Aubrey: "Block B is floating higher in the water. It must have the greater buoyant force acting on it."

Mary: "You are forgetting Newton's first law. Neither block is moving, so the buoyant force must balance the gravitational force in both cases. The buoyant forces must be equal to each other."

Cassandra: "Archimedes taught us that the buoyant force is *always* equal to the weight of the fluid displaced. Block A is displacing a lot more water than block B, so block A has the larger buoyant force."

Do you agree with any of these students?

ANSWER Cassandra is correct. Archimedes' principle *always* applies, regardless of whether an object sinks or floats. Block A displaces the most water, so it experiences the larger buoyant force. Mary starts out with correct ideas but then draws a faulty conclusion. The buoyant force on either block must equal the gravitational force on that block (by Newton's first law), so block A must be heavier. Because both blocks have the same volume, block A must be made of a denser wood. Perhaps block A is made of oak, and block B is made of pine.

like the one shown in Figure 12-11. If we put pressure gauges along the pipe, the surprising finding is that the pressure is lower in the narrow region of the pipe. If the fluid is not compressible, the fluid must be moving faster in the narrow region; that is, the same amount of fluid must pass by every point in the pipe, or it would pile up. Therefore, the fluid must flow faster in the narrow regions. This may lead one to conclude incorrectly that the pressure would be higher in this region. Swiss mathematician and physicist Daniel Bernoulli stated the correct result as a principle.

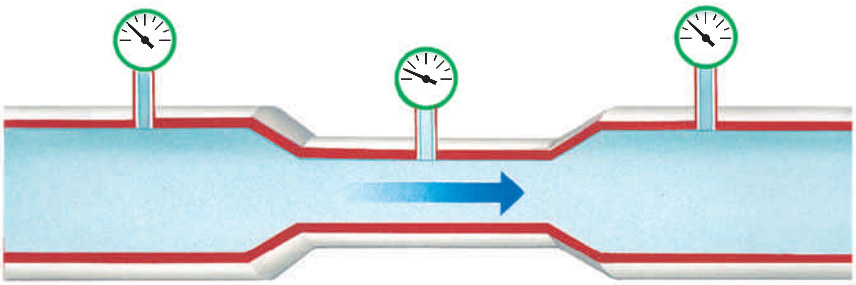


Figure 12-11 The pressure is smaller in the narrow region of the pipe where the velocity of the fluid is greater.

Figure 12-12 The "cube" of fluid entering the narrow region of the pipe must experience a net force to the right.

The pressure in a fluid decreases as its velocity increases.

◀ Bernoulli's principle

A tornado caused the difference in the air pressures inside and outside this house that tore off the roof.

We can understand **Bernoulli's principle** by "watching" a small cube of fluid flow through the pipe (Figure 12-12). The cube must gain kinetic energy as it speeds up entering the narrow region. Because there is no change in its gravitational potential energy, there must be a net force on the cube that does work on it. Therefore, the force on the front of the cube must be less than on the back. That is, the pressure must decrease as the cube moves into the narrow region. As the cube of fluid exits from the narrow region, it slows down. Therefore, the pressure must increase again.

There are many examples of Bernoulli's effect in our everyday activities. Smoke goes up a chimney partly because hot air rises but also because of the Bernoulli effect. The wind blowing across the top of the chimney reduces the pressure and allows the smoke to be pushed up. This effect is also responsible for houses losing roofs during tornadoes (or attacks by big bad wolves). When a tornado reduces the pressure on the top of the roof, the air *inside* the house lifts the roof off.

A fluid moving past an object is equivalent to the object moving in the fluid, so the Bernoulli effect should occur in these situations. A tarpaulin over the back of a truck lifts up as the truck travels down the road because of the reduced pressure on the outside surface of the tarpaulin produced by the truck moving through the air. This same effect causes your car to be sucked toward a truck as it passes you going in the opposite direction. The upper surfaces of airplane wings are curved so that the air has to travel farther to get to the back edge of the wing. Therefore, the air on top of the wing must travel faster than that on the underside and the pressure on the top of the wing is less, providing lift to keep the airplane in the air.

Summary

Density is an inherent property of a substance and is defined as the amount of mass in one unit of volume.

Elements combine into substances that can exist in four states of matter: solids, liquids, gases, and plasmas. The transitions between states occur when energy is supplied to or taken from substances. When a solid is heated above its melting point, interatomic bonds break to form a liquid in which atoms and molecules are free to move about. Upon further heating, the molecules totally separate to form a gas. In the plasma state, the atoms have been torn apart, producing charged ions and electrons. Although plasma is rare on Earth, it is the most common state in the universe.

The electric forces between atoms bind all materials together. If the atoms are ordered, a crystalline structure results. Liquids take the shape of their container, and most lack an ordered arrangement of their molecules. The intermolecular forces in a liquid create a surface tension that holds the molecules

Everyday Physics | *The Curve Ball*

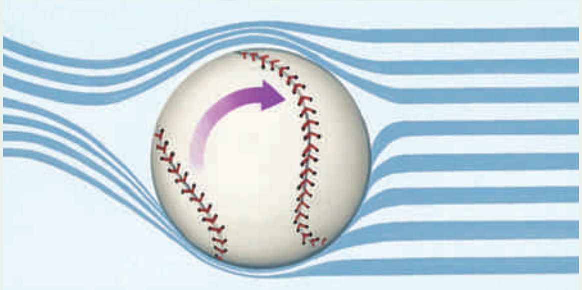
When a ball moves through air, strange things can happen. Perhaps the most common examples are the curve in baseball, the slice in golf, and the topspin serve in tennis. Isaac Newton wrote about the unusual behavior of spinning tennis balls, and baseball players and scientists have debated the behavior of the curve ball since the first baseball was thrown more than a hundred years ago. The balls naturally follow projectile paths because of gravity (Chapter 5), but it's the extra motion that is the bane of all batters.

Early on, the debate centered on whether the curve ball even existed. Scientists, believing that the only forces on the ball were gravity and air resistance (drag), argued that the curve ball must be just an optical illusion. "Not true!" retorted the baseball players. "It's like the ball rolled off a table just in front of the plate."

When there's a debate about the material world, the best procedure is to devise an experiment—that is, to ask the question of the material world itself. In the early 1940s, *Life* magazine commissioned strobe photos of a curve ball and concluded that the scientists were right: The curve ball is an optical illusion. Not to be outdone, *Look* magazine commissioned its own photos and concluded that the scientists (and *Life* magazine!) were wrong.

More recently, three scientists reexamined the question. They found a dark warehouse, a bank of strobe lights, and—most important—a professional pitcher. After careful analysis the verdict was clear: the ball does indeed curve away from the projectile path, and the deviation is created by the ball's spin. If the ball travels at 75 mph, it takes about $\frac{1}{2}$ second to travel the 60 feet to the batter. During this time, the ball rotates about 18 times and deviates from the projectile path by about 1 foot.

The direction of the deviation depends on the orientation of the spin. The deviation is always perpendicular to the axis of the spin; therefore, spin around a vertical axis moves the ball left or right. Because this would only change the point of contact with a horizontal bat, it is not very effective. Spin around a horizontal axis causes the ball to move up or down. Backspin (the bottom of the ball moving toward the batter) causes the ball to stay above the projectile path, which helps the batter. The best situation (for the pitcher!) is topspin. This increases the drop as the ball approaches the batter.

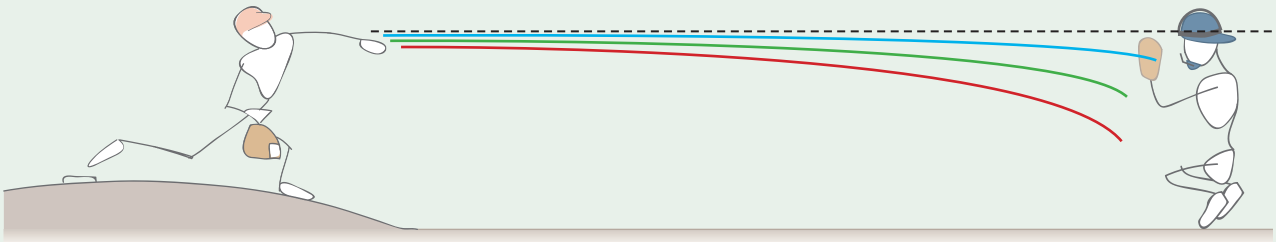


The spinning ball causes the airflow to deflect upward, imparting a downward force on the ball.

The question of when the ball deviates was also answered by this experiment. Batters have claimed for years that the ball travels along its normal path and then breaks at the last moment. Scientists claim that the forces—both gravity and the one caused by the spin—are constant; thus, the path is a continuous curve. Our study of projectile motion has shown that a ball falls farther during each succeeding second. This is compounded by the extra drop due to the spin. Thus, the vertical speed is much faster near the plate. But the drop is a continuous one; it does not abruptly change.

We are now left with the question of what causes the downward force. The baseball's cotton stitches—216 on a regulation ball—grab air, creating a layer of air that is carried around the spinning ball. (An insect sitting on the spinning ball would feel no wind—just as dust on a fan's blades is undisturbed by the fan's rotation.) To account for the force, we must look at the turbulence, or wake, behind the ball. The airflow over the top of the ball has a larger speed relative to the surrounding air and breaks up sooner than the airflow under the bottom, as shown in the figure. This causes the wake behind the ball to be shifted upward. According to Newton's third law, the momentum imparted to the wake in the upward direction causes an equal momentum to be imparted downward on the ball, and the curve ball drops.

Let the games begin!



The blue curve represents the ball's path due to its spin without any gravity. The green curve is the ball's path due to gravity without spin. The red curve shows the combined effect of spin and gravity.

to the liquid. A gas fills the container holding it, assuming its shape and volume. All gases are compressible and can be readily mixed with each other. The viscosity of a fluid determines how easily it pours and what resistance it offers to objects moving through it.

The pressure in a liquid or gas varies with depth because of the weight of the fluid above that point. At sea level the average atmospheric pressure is about 101 kilopascals (14.7 pounds per square inch).

An object in a fluid experiences a buoyant force equal to the weight of the fluid displaced; therefore, all objects appear to weigh less in water than in air. The buoyant force exists because the pressure in a fluid varies with depth. The pressure on the bottom surface of an object is greater than on its top surface. Objects less dense than the fluid float. The pressure in a moving fluid decreases with increasing speed.

CHAPTER 12 *Revisited*

The crystal's macroscopic shape results from a growth process that adds to the overall structure of the crystal, atom by atom. Study of these crystalline shapes gives scientists clues about the way atoms combine.

Key Terms

Archimedes' principle The buoyant force is equal to the weight of the displaced fluid.

Bernoulli's principle The pressure in a fluid increases as its velocity decreases.

buoyant force The upward force exerted by a fluid on a submerged or floating object. (See *Archimedes' principle*.)

crystal A material in which the atoms are arranged in a definite geometric pattern.

density A property of a material equal to the mass of the material divided by its volume. Density is measured in kilograms per cubic meter.

gas Matter with no definite shape or volume.

liquid Matter with a definite volume that takes the shape of its container.

plasma A highly ionized gas with equal numbers of positive and negative charges.

solid Matter with a definite size and shape.

viscosity A measure of the internal friction within a fluid.

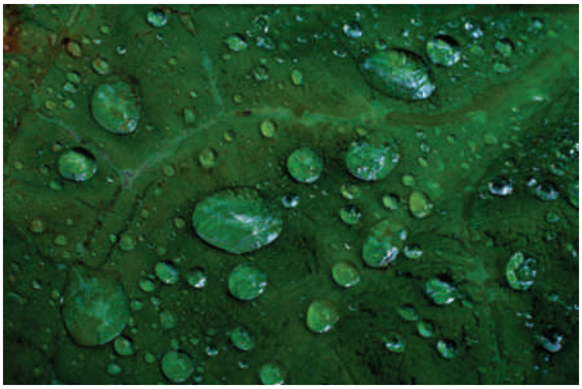
Questions and exercises are paired so that most odd-numbered are followed by a similar even-numbered.
Blue-numbered questions and exercises are answered in Appendix B.
indicates more challenging questions and exercises.
WebAssign Many Conceptual Questions and Exercises for this chapter may be assigned online at WebAssign.

Conceptual Questions

1. What are the four states of matter?
2. Is the average kinetic energy of the molecules in a liquid greater or smaller than in a solid of the same material? Why?
3. Does the aluminum in a soda can or in an automobile engine have the larger density? Why?
4. Which has a greater density, a tiny industrial diamond used in grinding powders or a 3-carat diamond in a wedding ring? Explain.
5. Aluminum and magnesium have densities of 2.70 and 1.75 grams per cubic centimeter, respectively. If you have equal masses of each, which one will occupy the larger volume? Explain.
6. Gold and silver have densities of 19.3 and 10.5 grams per cubic centimeter, respectively. If you have equal volumes of each, which one will have the larger mass? Explain.
7. Although the uranium atom is more massive than the gold atom, gold has the larger density. What does this tell you about the two solids?
8. People who live in cold climates know better than to turn off the heat in their homes in the winter without first draining the water out of the copper pipes. Explain why the pipes will burst if this is not done.
9. Are the crystal structures of ice and table salt the same? How do you know?

© Cengage Learning/George Semple

10. How does the crystal structure of mica differ from that of table salt?
11. How does the structure of diamond differ from that of graphite?
12. What does the observation that mica can be separated into thin sheets tell you about the crystal structure of mica?
13. When solids melt to form liquids, they retain their chemical identity. Which is stronger, the forces holding atoms together to form molecules or the forces holding the molecules together in a solid? Why?
14. Which is stronger in a typical liquid, the intermolecular forces (those between molecules) or the interatomic forces (those holding the molecule together)? What evidence do you have for your answer?
15. What shape would you expect a drop of water to take if it were suspended in the air in the space shuttle?
16. Why does water bead up when it is spilled on a waxed floor?



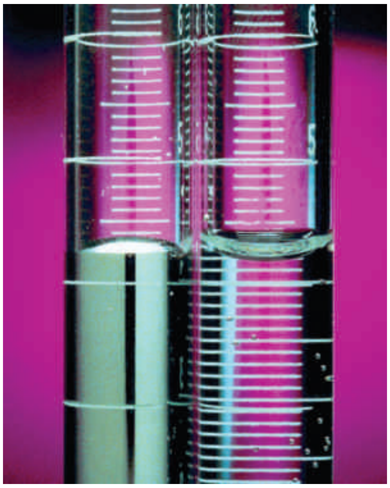
© Photodisc Green/Getty Images

17. If you fill a glass with water level with the top of the glass, you can carefully drop several pennies into the glass without spilling any water. How do you explain this?

© Cengage Learning/George Semple

18. Why does soapy water bead up less than plain water on a countertop?

19. When you half-fill a glass with water, the water creeps up where it meets the glass. What can you conclude about the relative strengths of the intermolecular forces between the water molecules and the adhesive forces between the water molecules and the glass?



© Cengage Learning/Charles D. Winters

Questions 19 and 20

20. When you half-fill a glass with mercury, the mercury curls down where it meets the glass. What can you conclude about the relative strengths of the interatomic forces between the mercury atoms and the adhesive forces between the mercury atoms and the glass? (*Caution:* Mercury is toxic and should *not* be handled.)

21. How does a gas differ from a plasma?

22. What state of matter forms the Van Allen belts?

23. Use the concept of pressure to explain why it is more comfortable to walk in bare feet across a paved driveway than across a gravel driveway.

24. A closed book that is initially lying flat on a desk is turned to balance on its spine. Compare the forces exerted by the book on the table in the two orientations. Compare the pressures exerted by the book on the table in the two orientations.

25. You place a small amount of water in a 1-gallon can and bring it to a rapid boil. You take the can off the stove and screw the cap on tightly (the order is important here!). As the steam inside cools, it condenses back into water, causing the can to collapse. Why?

26. At sea level each square inch of surface experiences a force of 14.7 pounds due to air pressure. You are carrying a cookie sheet loaded with chocolate chip cookies. The surface area of the cookie sheet is 250 square inches, which means that the downward force exerted by the air column above the cookie sheet is 3675 pounds! Why doesn't the cookie sheet feel this heavy?

27. You repeat von Guericke's experiment (see Figure 12-7) using somewhat smaller half spheres and find that two teams of eight horses are just strong enough to pull the half spheres apart. You then transport the apparatus to Denver, which is at an elevation of 1 mile. Will you need more or fewer horses to pull the half spheres apart? Why?

28. A classmate explains that if your bathroom scale reads 150 pounds when you stand on it at sea level, it will read only 75 pounds on the top of an 18,000-foot mountain, where atmospheric pressure is reduced by one-half. What is wrong with your classmate's reasoning? Would you expect the scale reading to be reduced at all as a result of the decrease in atmospheric pressure?

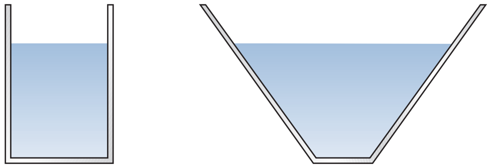
29. On a weather map, you see areas of low pressure marked with an L and areas of high pressure marked with an H. By convention, the pressures reported are always corrected to the value they would have at sea level. If this were not the case, what letter would you see permanently above the mile-high city of Denver? Explain.

30. Mountaineers often carry altimeters that measure altitude by measuring atmospheric pressure. If a low-pressure weather system moves in, will the altimeter report an altitude that is higher or lower than the true altitude? Explain.

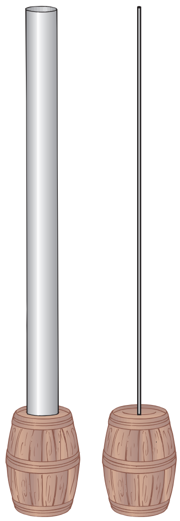
31. Are your ears going to hurt more because of water pressure if you are swimming 12 feet down in your swimming pool or 12 feet down in the middle of Lake Superior? Explain.

32. How was it possible for the little Dutch boy to hold back the entire North Sea by putting his finger in the dike?

33. Compare the pressures at the bottom of the two glasses shown in the following figure. Assume that both are filled to the same depth with the same fluid.



34. Two identical wooden barrels are fitted with long pipes extending out their tops. The pipe on the first barrel is 1 foot in diameter, and the pipe on the second barrel is only $\frac{1}{2}$ inch in diameter. When the larger pipe is filled with water to a height of 20 feet, the barrel bursts. To burst the second barrel, will water have to be added to a height less than, equal to, or greater than 20 feet? Explain.



35. Fresh water has a density of 1000 kilograms per cubic meter at 4°C and 998 kilograms per cubic meter at 20°C. In which temperature water would you feel the greater pressure at a depth of 10 meters? Why?

36. Salt water is more dense than fresh water. This means that the mass of 1 cubic centimeter of salt water is larger than that of 1 cubic centimeter of fresh water. Would a scuba diver have to go deeper in salt water or in fresh water to reach the same pressure? Why?

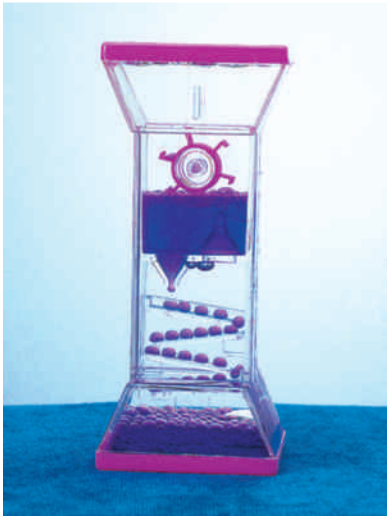
37. Why can't water be "sucked" to a height greater than 10 meters even with a very good suction pump?

38. At sea level even a perfect vacuum can raise water only 10 meters up a straw. At an elevation of 5000 feet in Bozeman, Montana, can water be raised to a height greater than, equal to, or less than 10 meters? Explain your reasoning.

39. If you have a water well that is much deeper than about 5 meters, you put the pump at the bottom of the well and have it push the water up. Why is this better than placing the pump at the top?

40. You place a long straw in a glass of water and find that, no matter how hard you suck, you cannot drink the water. You place the same straw in an unknown liquid X and find that you can drink. If you combine liquid X and water together in a glass, which one will float on the surface?

41. Some toys contain two different-colored liquids that do not mix. If the purple liquid always sinks in the clear liquid as shown in the toy in the following figure, what can you say about the densities of the liquids?



© Cengage Learning/George Semple

42. Spilled gasoline can sometimes be seen as a colorful film on the top of rain puddles. What does this tell you about the density of gasoline?

43. Salt water is slightly more dense than fresh water. Will a boat float higher in salt water or fresh water?

44. Use Archimedes' principle to explain why an empty freighter sits higher in the water than a loaded one.

45. Salt water is slightly more dense than fresh water. Will a 50-ton ship feel a greater buoyant force floating in a freshwater lake or in the ocean?

46. Salt water is slightly more dense than fresh water. Will a 12-pound bowling ball feel a greater buoyant force sitting on the bottom of a freshwater lake or on the bottom of the ocean?

47. When you blow air from your lungs, you are changing both your mass and your volume. Which of these effects explains why this causes you to sink to the bottom of a swimming pool?

48. What happens to the depth of a scuba diver who takes a particularly deep breath?

49. Use the data in Table 12-1 to determine whether a block of lead would float in liquid mercury. What about a block of gold? (*Caution:* Do *not* try this experiment; mercury is very toxic!)

50. Use the data in Table 12-1 to determine which would float higher in liquid mercury, a block of copper or a block of silver.

51. A submarine could be made to surface by either increasing the buoyant force or decreasing the weight. When a submarine's ballast tanks are blown out, which is happening?

52. A scuba diver achieves neutral buoyancy by adjusting the volume of air in her air vest so that the buoyant force equals her weight. If she then kicks her feet and swims down an additional 20 feet, will the net force now be upward, zero, or downward? Explain.

53. You have two cubes of the same size, one made of aluminum and the other of lead. Both cubes are allowed to sink to the bottom of a water-filled aquarium. Which cube, if either, experiences the greater buoyant force? Why?

54. You have two cubes of the same size, one made of wood and the other of aluminum. Both cubes are placed in a water-filled aquarium. The wooden block floats, and the aluminum block sinks. Which cube, if either, experiences the greater buoyant force?

55. An ice cube is floating in a glass of water. Will the water level in the glass rise, go down, or stay the same as the ice cube melts? Why?

56. You are sitting in a boat in your swimming pool. There are six gold bricks in your boat. (You are rich!) If you throw the gold into the swimming pool, does the water level in the pool rise, fall, or stay the same? Explain.

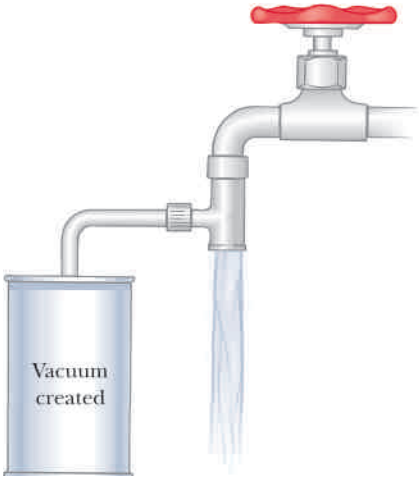
57. You place a dime flat on a tabletop a couple of inches from the edge. With your mouth near the edge of the table, you blow sharply across the top of the dime. Why does the dime pop up in the air? Try this.

58. Why does your car get pulled sideways when a truck passes you going in the opposite direction on a two-lane highway?

59. Why do table-tennis players put a lot of topspin on their shots?

© Redlink Production/Corbis/Jupiterimages

60. A partial vacuum can be created by installing a pipe at a right angle to a water faucet and turning on the water, as shown in the following figure. What is the physics behind this?



61. The Green Building at the Massachusetts Institute of Technology (MIT) is a tall tower built on an inverted U-shaped base that is open to the Charles River Basin. Why might the doors in the opening have opened "by themselves" on windy days before revolving doors were installed to correct the design flaw?

Gary Bonner

62. Why would an aneurysm (a widening of an artery) be especially subject to rupturing?

Exercises

63. What is the density of a substance that has a mass of 27 g and a volume of 10 cm^3? Use Table 12-1 to identify this substance.

64. A small ball has a mass of 6.75 g and a volume of 0.3 cm^3. Can you identify the material using Table 12-1?

65. A bowling trophy has a mass of 180 g. When placed in water, the trophy displaces 600 cm^3. What is the average density of the trophy?

66. If Archimedes' crown had a mass of 1 kg and a volume of 120 cm^3, was the crown made of pure gold? Explain.

67. A solid ball with a volume of 0.4 m^3 is made of a material with a density of 3000 kg/m^3. What is the mass of the ball?

68. What is the mass of a lead sinker with a volume of 3 cm^3?

69. Given that most people are just about neutrally buoyant, it is reasonable to estimate the density of the human body to be about that of water. Use this assumption to find the volume of a 70-kg person.

70. A cube with a mass of 48 g is made from a metal with a density of 6 g/cm^3. What is the volume of the cube and the length of each edge?

71. If 1000 cm^3 of a gas with a density of 0.0009 g/cm^3 condenses to a liquid with a density of 0.9 g/cm^3, what is the volume of the liquid?

72. A cube of ice, 10 cm on each side, is melted into a measuring cup. What is the volume of the liquid water?

73. Calculate the weight of a column of fresh water with cross-sectional area 1 m^2 and height 10 m. What pressure does this create at the bottom of the column of water? How does this compare to atmospheric pressure?

74. Calculate the height of a column of mercury with cross-sectional area 1 m^2 such that it has the same weight as the column of water in Exercise 73.

75. Given that atmospheric pressure drops by a factor of 2 for every gain in elevation of 18,000 ft, what is the height of a mercury column in a barometer located in an unpressurized compartment of an airliner flying at 36,000 ft?

76. Two barometers are made with water and mercury. If the mercury column is 30 in. tall, how tall is the water column?

77. Each cubic inch of mercury has a weight of 0.5 lb. What is the pressure at the bottom of a column of mercury 30 in. tall if there is a vacuum above the mercury?

78. If 1 m^3 of water has a mass of 1000 kg, what is the pressure at a depth of 150 m? Is the atmospheric pressure important?

79. An object has a mass of 150 kg and a volume of 0.2 m^3. What is its average density? Will this object sink or float in water?

80. Will an object with a mass of 1000 kg and a volume of 1.6 m^3 float?

81. A 500-g wooden block is lowered carefully into a completely full beaker of water and floats. What is the weight of the water, in newtons, that spills out of the beaker?

82. A 400-cm^3 block of aluminum ($D = 2.7$ g/cm^3) is lowered carefully into a completely full beaker of water. What is the weight of the water, in newtons, that spills out of the beaker?

83. A ball of wax is lowered carefully into a completely full beaker of water, where it floats. This causes 18 cm^3 of water to spill out. The same ball of wax is then lowered carefully into a completely full beaker of ethyl alcohol ($D = 0.79$ g/cm^3), where it sinks, causing 20 cm^3 of alcohol to spill out. Which of these two experiments allows you to find the wax's mass, and which allows you to find its volume? Find the density of the wax.

84. A yellow object is lowered carefully into a completely full beaker of water, where it floats. This causes 28 cm^3 of water to spill out. The same object is then lowered carefully into a completely full beaker of gasoline ($D = 0.68$ g/cm^3), where it sinks, causing 40 cm^3 of gasoline to spill out. In which liquid does the yellow object experience the greater buoyant force?

85. A cubic meter of copper has a mass of 8930 kg. The block of copper is lowered into a lake by a strong cable until the block is completely submerged. Draw a free-body diagram for the block. Find the buoyant force on the block and the tension in the cable.

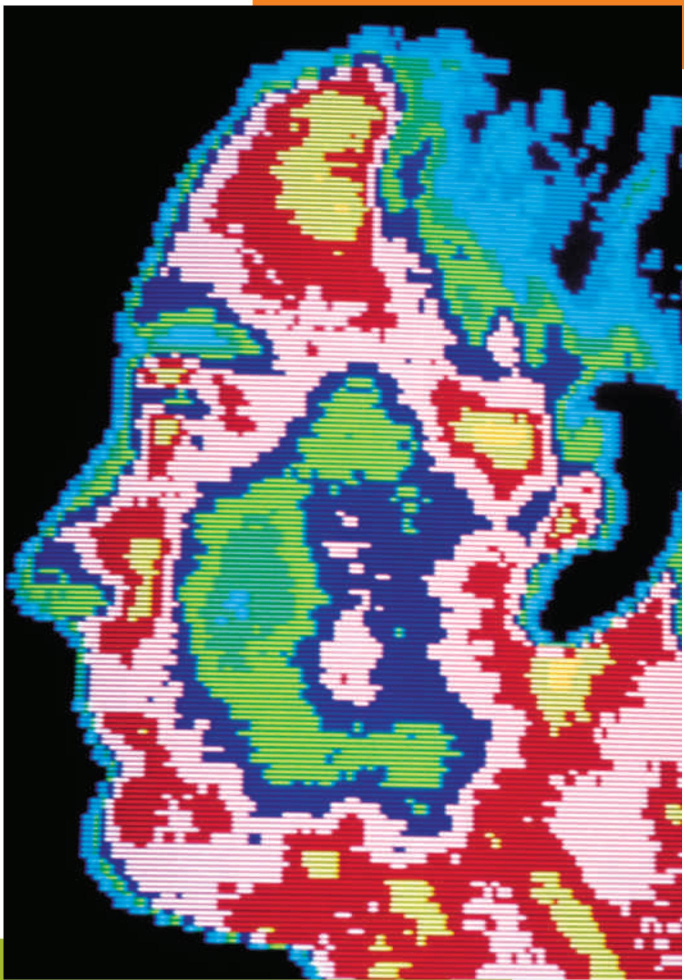
86. A ball fully submerged in a bathtub has a volume of 5 cm^3 and a mass of 30 g. Draw a free-body diagram for the ball. What is the normal force of the tub on the ball?

13

Thermal Energy

▶This false-color thermograph of a human head shows the temperature variations of the surface. What factors control the rate at which radiation is emitted or absorbed and the resulting temperature changes?

(See page 278 for the answer to this question.)



Mark Harmel/FPG/Getty

False-color thermograph of a human head.

IF we examine any system of moving objects carefully or if we look at it long enough, we find that mechanical energy is not conserved. A pendulum bob swinging back and forth does in fact come to rest. Its original mechanical energy disappears.

Other examples show the same thing. Rub your hands together. You are doing work—applying a force through a distance—but clearly your hands do not fly off with some newfound kinetic energy. Similarly, take a hammer and repeatedly strike a metal surface. The moving hammer has kinetic energy, but on hitting the surface, its kinetic energy disappears. What happens to the energy? It is not converted to potential energy as happened in Chapter 7 because the energy doesn't reappear. So either the kinetic energy truly disappears and total energy is not conserved, or it is transferred into some form of energy that is not a potential energy.

There are similarities in the preceding examples. When you rub your hands together, they feel hot. The metal surface and the hammer also get hotter when they are banged together. The pendulum bob is not as obvious; the interactions are between the bob and the surrounding air molecules and between the string and the support. But closer examination shows that, once again, the system gets hotter.

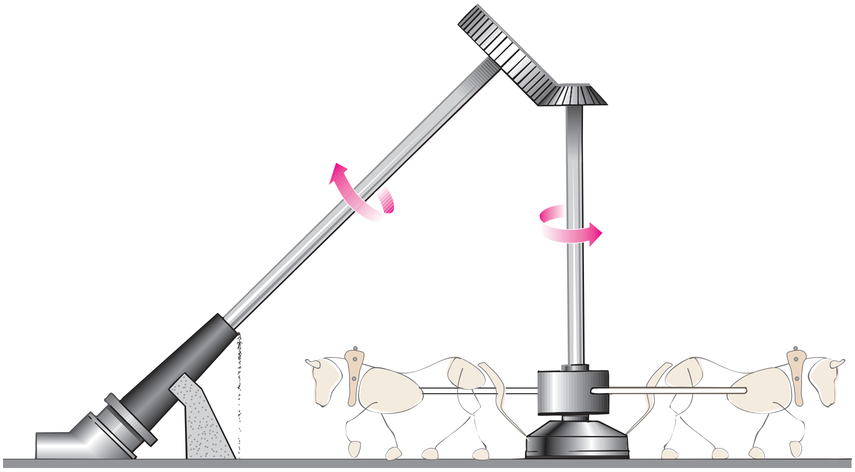
At first glance it is tempting to suggest that temperature, or maybe the change in temperature, could be equated with the lost energy. However, neither of these ideas works. If the same amount of energy is expended on a collection of different objects, the resulting temperature increases are not equal. Suppose, for example, that we rub two copper blocks together. The temperature of the copper blocks increases. If we repeat the experiment by expending the same amount of mechanical energy with two aluminum blocks, the change in temperature will not be the same. The temperature change is an indication that something has happened, but it is not equal to the lost energy.

The Nature of Heat

Early ideas about the nature of heat centered on the existence of a fluid that was supposedly transferred between objects at different temperatures. Over centuries people had noted that a kettle of water could become hot, boil, and turn to steam or that a snowbank could absorb the Sun's heat for an extended period and slowly melt. Fire transferred something to the hot water to make it boil; sunshine imparted something to the snow to liquefy it over time. This "fluid" was studied intensively in the era of early steam-engine technology. It became known as *caloric,* from the Latin *calor,* meaning "heat." It was invisible and presumably massless because experimenters could not detect any changes in the mass of an object that was heated.

Count Rumford, an 18th-century British scientist, pioneered a study of work and heat. At that time he was in charge of boring cannons at a military arsenal in Munich and was struck by the enormous amount of heat produced during the boring process. Rumford decided to investigate this. He placed a dull boring tool and a brass cylinder in a barrel filled with cold water. The boring tool was forced against the bottom of the cylinder and rotated by two horses. These are the results described by Rumford:

> **At the end of 2 hours and 30 minutes it [the water in the barrel] actually boiled! . . . It would be difficult to describe the surprise and astonishment expressed by the countenances of the by-standers, on seeing so large a quantity of cold water heated, and actually made to boil without any fire.**



Rumford investigated the nature of heat while boring cannons.

Rumford showed that large quantities of heat could be produced by mechanical means without fire, light, or chemical reaction. (This is a large-scale version of the simple hand-rubbing experiment.) The importance of his experiment was the demonstration that the production of heat seemed inexhaustible. As long as the horses turned the boring tool, heat was generated without any limitation. He concluded that anything that could be produced without limit could not possibly be a material substance. Heat was not a fluid but something generated by motion.

In our modern physics world view, **heat** is energy *flowing* between two objects because of a difference in temperature. We measure the amount of energy gained or lost by an object by the resulting temperature change in the object. By convention, 1 **calorie** is defined as the amount of heat that raises the temperature of 1 gram of water by 1°C. In the U.S. customary system, the unit of heat, called a **British thermal unit** (Btu), is the amount of energy needed to change the temperature of 1 pound of water by 1°F. One British thermal unit is approximately equal to 252 calories.

Q: How many calories are required to raise the temperature of 8 grams of water by 5°C?

A: To raise the temperature of 1 gram by 5°C requires 5 calories. Therefore, 8 grams requires 5 calories/gram $\times$ 8 grams = 40 calories.

Mechanical Work and Heat

Extended presentation available in the *Problem Solving* supplement

The Rumford experiment used the *work* supplied by the horses to raise the temperature of the water, clearly demonstrating an equivalent way of "heating" the water. The water got hotter as if it were heated by a fire, but there was no fire.

There is a close connection between work and heat. Both are measured in energy units, but neither resides in an object. In Chapter 7 we saw that work was a measure of the energy "flowing" from one form to another. For example, the gravitational force does work on a free-falling ball, causing its kinetic energy to increase—thus, potential energy changes to kinetic energy. Similarly, heat does not reside in an object but flows into or out of an object,

Q: Because joules and calories are both energy units, do we need to retain both of them?

A: No. However, both are currently used for historical reasons. Europeans are much further along than Americans in converting from Calories to kilojoules in the labeling of food.

changing the internal energy of the object. This internal energy is sometimes known as **thermal energy**, and the area of physics that deals with the connections between heat and other forms of energy is called **thermodynamics**.

1 calorie = 4.2 joules ▶

Although Rumford's experiment hinted at the equivalence between mechanical work and heat, James Joule uncovered the quantitative equivalence 50 years later. Joule's experiment used a container of water with a paddle-wheel arrangement like that shown in Figure 13-1. The paddles are connected via pulleys to a weight. As the weight falls, the paddle wheel turns, and the water's temperature goes up. The potential energy lost by the falling weight results in a rise in the temperature of the water. Because Joule could raise the water temperature by heating it or by using the falling weights, he was able to establish the equivalence between the work done and the heat transferred. Joule's experiment showed that 4.2 joules of work are equivalent to 1 calorie of heat.

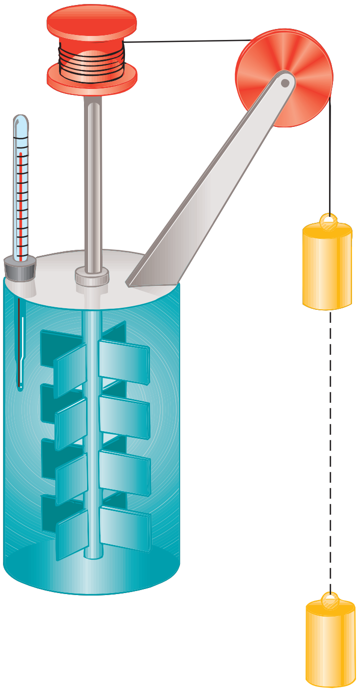


Figure 13-1 Joule's apparatus for determining the equivalence of work and heat. The decrease in the gravitational potential energy of the falling mass produces an increase in the energy of the water.

There are other units of energy. The Calorie used when referring to the energy content of food is not the same as the calorie defined here. The food Calorie (properly designated by the capital C to distinguish it from the one used in physics) is equal to 1000 of the physics calories. A piece of pie rated at 400 Calories is equivalent to 400,000 calories of thermal energy, or nearly 1.7 million joules of mechanical energy.

Temperature Revisited

If we bring two objects at different temperatures into contact with each other, there is an energy flow between them, with energy flowing from the hotter object to the colder. We know from the structure of matter (Chapter 11) that the molecules of the hotter object have a higher average kinetic energy. Therefore, on the average, the more-energetic particles of the hotter object lose some of their kinetic energy when they collide with the less-energetic particles of the colder object. The average kinetic energy of the hotter object's particles decreases and that of the colder object's particles increases until they become equal. On a macroscopic scale, the temperature changes for each object: the hotter object's temperature drops, and the colder object's temperature rises. The flow of energy stops when the two objects reach the same temperature, a condition known as **thermal equilibrium**. Atomic collisions still take place, but on average the particles do not gain or lose kinetic energy.

Suppose that we have two objects, labeled A and B, that cannot be placed in thermal contact with each other. How can we determine whether they would be in thermal equilibrium if we could bring them together? Let's assume that we have a third object, labeled C, that can be placed in thermal contact with A and that A and C are in thermal equilibrium. If C is now placed in thermal contact with B and if B and C are also in thermal equilibrium, then we can conclude that A and B are in thermal equilibrium. This is summarized by the statement of the **zeroth law of thermodynamics**:

zeroth law of thermodynamics ▶

If objects A and B are in thermal equilibrium with object C, then A and B are in thermal equilibrium with each other.

Joule | *A New View of Energy*

James Prescott Joule (1818–1889) was the second son of a family of wealthy brewers in the village of Salford near Manchester, England, an industrial region. Joule was tutored as a youngster by John Dalton, a noted, elderly chemist, and determined early in life to pursue physical science as a serious hobby.

The Royal Society, London/The Bridgeman Art Library

James Prescott Joule

Today Joule is remembered for his experiments and theories on work, energy, and heat. Michael Faraday was an early, major source of inspiration, and Joule conducted experiments on heating in conducting wires—mostly made of copper or platinum. His energy sources were voltaic batteries and the dynamo. This early work earned him the reputation of a pioneer in battery design and efficiency. His views on the equivalence of heat and work derived from these early electrochemical experiments.

Manchester was a city of steam engines, so it was natural that Joule and his friends in the local scientific and engineering group would discuss theories of heat and means of improving engine performance. His own work led in a general way to the concept of thermal efficiency, but he contributed little to steam technology because he thought engineers were better suited to technical improvements. The physicists' job was to extend the power of theory.

Joule excelled in precision measurement. He was fortunate that a local Manchester firm could manufacture calorimeters and thermometers for him. By 1840 he had calibrated temperature differences to an accuracy of 0.01°F, and in later experiments he used calibrations one-half this size. Many of his peers at that time underestimated the importance of precision measurements. Joule's appointment to the first major British commission on scientific standards validated his efforts.

As his conceptual grasp of the issues evolved, Joule recognized and measured the equivalence between mechanical work and heat in several ways. One of the most striking was the accurate measurement of the increase in temperature of water as it fell over a waterfall into a pool. His first observations were in France, but he speculated about Niagara Falls, which he had not visited, and accurately predicted the increase.

At a meeting during which Joule delivered a paper that most in the audience did not understand completely, he met an important collaborator, William Thomson, known later as Lord Kelvin. Kelvin's mathematical skills combined with Joule's careful measurements solidified understanding of the first and second laws of thermodynamics. Among other contributions, their work presaged the rise of mechanical refrigeration later in the 19th century. Current concepts of energy and the use of precision measurements owe much to the quiet and unassuming work performed by James Prescott Joule.

—*Pierce C. Mullen, historian and author*

Sources: Mary B. Hesse, *Forces and Fields: The Concept of Action at a Distance in the History of Physics* (New York: Philosophical Library, 1962); Henry John Steffens, *James Prescott Joule and the Concept of Energy* (New York: Science History Publications, 1979).

Although this statement may seem to be so obvious that it is not worth elevating to the stature of a law, it plays a fundamental role in thermodynamics because it is the basis for the definition of temperature. Two objects in thermal equilibrium have the same temperature. On the other hand, if two objects are not in thermal equilibrium, they must have different temperatures. The zeroth law was developed later in the history of thermodynamics but labeled with a zero because it is more basic than the other laws of thermodynamics.

Heat, Temperature, and Internal Energy

Heat and temperature are not the same thing. Heat is an energy, whereas temperature is a macroscopic property of an object. Two objects can be at the same temperature (the same average atomic kinetic energy) and yet transfer vastly different amounts of energy to a third object. For example, a swimming pool of water and a coffee cup of water at the same temperature can melt very different amounts of ice.

When we consider the total microscopic energy of an object—such as translational and rotational kinetic energies, vibrational energies, and the energy stored in molecular bonds—we are talking about the **internal energy** of the object. There are two ways of increasing the internal energy of a system. One way is to heat the system; the other is to do work on the system. The law of conservation of energy tells us that the total change in the internal energy of the system is equal to the change due to the heat added to the system plus that due to the work done on the system. This is called the **first law of thermodynamics** and is really just a restatement of the law of conservation of energy.

first law of thermodynamics ▶

The increase in the internal energy of a system is equal to the heat added plus the work done on the system.

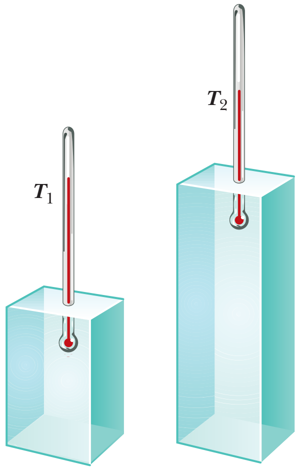


Figure 13-2 Adding equal amounts of heat to different amounts of a material produces different temperature changes.

This law sheds more light on the nature of internal energy. Let's assume that if 10 calories of heat are added to a sample of gas, its temperature rises by 2°C. If we add the same 10 calories to a sample of the same gas that has twice the mass, we discover that the temperature rises by only 1°C (Figure 13-2). Adding the same amount of heat does not produce the same rise in temperature. This makes sense because the larger sample of gas has twice as many particles, and therefore each particle receives only half as much energy on the average. The average kinetic energy, and thus the temperature, should increase by half as much. An increase in the temperature is an indication that the internal energy of the gas has increased, but the mass must be known to predict how much it increases.

Absolute Zero

The temperature of a system can be lowered by removing some of its internal energy. Because there is a limit to how much internal energy can be removed, it is reasonable to assume that there is a lowest possible temperature. This temperature is known as **absolute zero** and has a value of −273°C, the same temperature used to define the zero of the Kelvin scale.

The existence of an absolute zero raised the challenge of experimentally reaching it. The feasibility of doing so was argued extensively during the first three decades of the 20th century, and scientists eventually concluded that it was impossible. This belief is formalized in the statement of the **third law of thermodynamics**:

third law of thermodynamics ▶

Absolute zero may be approached experimentally but can never be reached.

There appears to be no restriction on how close experimentalists can get, only that it cannot be reached. Small systems in low-temperature laboratories have reached temperatures closer than a few billionths of a degree to absolute zero.

A substance at absolute zero has the lowest possible internal energy. Originally, it was thought that all atomic motions would cease at absolute zero. The development of quantum mechanics (Chapter 24) showed that all motion does not cease; the atoms sort of quiver with the minimum possible motion. In this state the atoms are packed closely together. Their mutual binding forces arrange them into a solid block.

Specific Heat

Suppose we have the same number of molecules of two different gases, and each gas is initially at the same temperature. If we add the same amount of heat

Figure 13-3 Three forms of internal energy for a diatomic molecule.

to each gas, we find that the temperatures do not rise by the same amount. Even though the gases undergo the same change in their internal energies, their molecules do not experience the same changes in their average translational kinetic energies. Some of the heat appears lost. Actually, the heat is transformed into other forms of energy. If the gas molecules have more than one atom, part of the internal energy is transformed into rotational kinetic energy of the molecules and part of it can go into the vibrational motion of the atoms (Figure 13-3). Only a small fraction of the increase in internal energy for most real gases goes into increasing the average kinetic energy that shows up as an increase in temperature.

The amount of heat it takes to increase the temperature of an object by 1°C is known as the **heat capacity** of the object. The heat capacity depends on the amount and type of material used to construct the object. An object with twice the mass will have twice the heat capacity, provided both objects are made of the same material.

We can obtain an intrinsic property of the material that does not depend on the size or shape of an object by dividing the heat capacity by the mass of the object. This property is known as the **specific heat** and is the amount of heat required to increase the temperature of 1 gram of the material by 1°C.

By definition, the specific heat of water is numerically 1; that is, 1 calorie raises the temperature of 1 gram of water by 1°C. The specific heat for a given material in a particular state depends slightly on the temperature but is usually assumed to be constant. The specific heats of some common materials are given in Table 13-1. Notice that the SI units for specific heat are joules per kilogram-kelvin. These are obtained by multiplying the values in calories per gram-degree Celsius by 4186. Note also that the value for water is quite high compared with most other materials.

Table 13-1 *Specific Heats for Various Materials*

Material	Specific Heat (cal/g · °C)	Specific Heat (J/kg · K)
Solids		
Aluminum	0.215	900
Copper	0.092	385
Diamond	0.124	519
Gold	0.031	130
Ice	0.50	2090
Silver	0.057	239
Liquids		
Ethanol	0.75	3140
Mercury	0.033	138
Water	1.00	4186
Gases		
Air	0.24	1000
Helium	1.24	5190
Nitrogen	0.25	1040
Oxygen	0.22	910

Q: What is the rise in temperature when 20 calories is added to 10 grams of ice at −10°C?

A: This is the same as adding 2 calories to each gram. Because $\frac{1}{2}$ calorie is required to raise the temperature of 1 gram of ice by 1°C, the 2 calories will raise its temperature by 4°C.

When we bring two different objects into thermal contact with each other, they reach thermal equilibrium but don't normally experience the same changes in temperature because they typically have different heat capacities. For example, when unequal amounts of hot and cold water are mixed together, the equilibrium temperature will not be midway between the hot

WORKING IT OUT | *Specific Heat*

The specific heat c is obtained by dividing the heat Q added to the material by the product of the mass m and the resulting change in temperature ΔT:

$$c = \frac{Q}{m\Delta T}$$

For example, if 11 cal is required to raise the temperature of an 8-g copper coin 15°C, we can calculate the specific heat of copper:

$$c = \frac{Q}{m\Delta T} = \frac{11 \text{ cal}}{(8 \text{ g})(15°\text{C})} = 0.092 \text{ cal/g} \cdot °\text{C}$$

Note that this agrees with the entry in Table 13-1.

We can rearrange our definition of specific heat to obtain an expression for the heat required to change the temperature of an object by a specific amount. For instance, suppose that you have a cup of water at room temperature that you want to boil. How much heat will this require? Let's assume that the cup contains $\frac{1}{4}$ L of water at 20°C and that we can ignore the heating of the cup itself. The mass of the water is 250 g, and the boiling point of water is 100°C at 1 atm. Therefore, the temperature change is 80°C, and we have

$$Q = cm\Delta T = \left(1 \frac{\text{cal}}{\text{g} \cdot °\text{C}}\right)(250 \text{ g})(80°\text{C}) = 20{,}000 \text{ cal} = 20 \text{ kcal}$$

The 20 kcal of energy must be supplied by the stove or microwave oven.

FLAWED REASONING

A lab manual asks students to mix 400 grams of warm ethanol at 60°C with 300 grams of room-temperature water at 20°C. Before performing this experiment, two students are making predictions for the final temperature of the mixture.

Christian: "The final temperature will be *higher* than 40°C. If the masses were equal, the final temperature would be halfway between 20°C and 60°C, but there is more ethanol than water."

Shannon: "No, the final temperature of the mixture will be *lower* than 40°C. Water has a higher specific heat, so the water will have a smaller change in temperature."

Both of these students are wrong. **Find the flaw in their reasoning.**

ANSWER Christian is focusing on the relative masses, whereas Shannon is focusing on the relative specific heats. Both factors play a role in determining the heat capacity of an object. The equilibrium temperature will be closer to the initial temperature of the fluid with the larger heat capacity. The heat capacities C of the ethanol and water are as follows:

$$C_{ethanol} = c_{ethanol} m_{ethanol} = \left(0.75 \frac{\text{cal}}{\text{g} \cdot °\text{C}}\right)(400 \text{ g}) = 300 \frac{\text{cal}}{°\text{C}}$$

$$C_{water} = c_{water} m_{water} = \left(1 \frac{\text{cal}}{\text{g} \cdot °\text{C}}\right)(300 \text{ g}) = 300 \frac{\text{cal}}{°\text{C}}$$

In this example both fluids have the same heat capacity, so the final equilibrium temperature will be 40°C, midway between the two initial temperatures.

and cold temperatures, but closer to the initial temperature of the larger sample. However, conservation of energy tells us that the heat lost by the hotter object is equal to the heat gained by the colder object. (We're assuming that no energy is lost to the environment.)

The specific heats of the materials on Earth's surface account for the temperature extremes lagging behind the season changes. The first day of summer in the Northern Hemisphere usually occurs on June 21. On this day the soil receives the largest amount of solar radiation because it is the longest day of the year and the sunlight arrives closest to the vertical. And yet the hottest days of summer typically occur several weeks later. It takes time for the ground to warm up because it requires a lot of energy to raise its temperature each degree.

Change of State

We continue our investigation of internal energy by continually removing energy from a gas and watching its temperature. If we keep the pressure constant, the volume and temperature of the gas decrease rather smoothly until the gas reaches a certain temperature. At this temperature there is a rapid drop in volume and *no* change in temperature. Drops of liquid begin to form in the container. As we continue to remove energy from the gas, more and more liquid forms, but the temperature remains the same. When all the gas has condensed into liquid, the temperature drops again (Figure 13-4). The change from the gaseous state to the liquid state (or from the liquid to the solid), or vice versa, is known as a **change of state.**

While the gas was condensing into a liquid, energy was continually leaving the system, but the temperature remained the same. Most of this energy came from the decrease in the electric potential energy between the molecules as they got closer together to form the liquid. This situation is analogous to the release of gravitational potential energy as a ball falls toward Earth's surface. The energy that must be released or gained per unit mass of material is known as the **latent heat.** The values of the latent heat for melting and vaporization are given in Table 13-2.

The same processes occur when you heat a liquid. If you place a pan of water on the stove, the temperature rises until the water begins to boil. The temperature then remains constant as long as the water boils. It doesn't matter whether the water boils slowly or rapidly. (Because the rate at which foods cook depends only on the temperature of the water, you can conserve energy

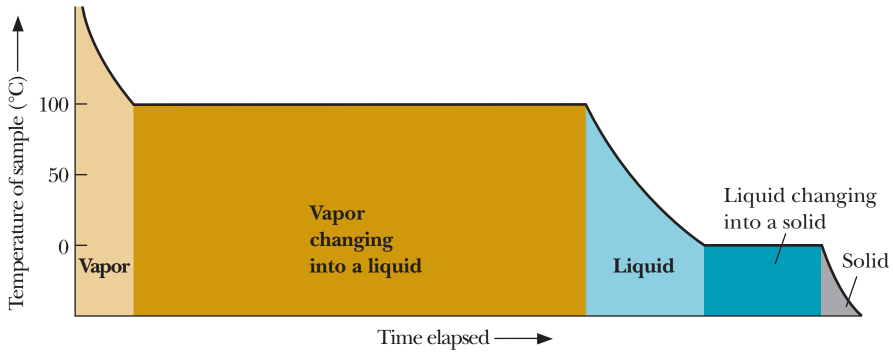


Figure 13-4 A graph of the temperature of water versus time as thermal energy is removed from the water. Notice that the temperature remains constant while the steam condenses to liquid water and while the liquid water freezes to form ice.

Table 13-2 *Melting Points, Boiling Points, and Latent Heats for Various Materials*

		Latent Heat (Melting)			Latent Heat (Vaporization)	
Material	**Melting Point (°C)**	**(kJ/kg)**	**(cal/g)**	**Boiling Point (°C)**	**(kJ/kg)**	**(cal/g)**
Nitrogen	−210	25.7	6.14	−196	199	47.5
Oxygen	−218	13.8	3.3	−183	213	50.9
Water	0	334	79.8	100	2257	539
Aluminum	660	396	94.6	2467	10,900	2600
Gold	1064	63	15	2807	1710	409

by turning the heat down as low as possible while still maintaining a boil.) During the change of state, the additional energy goes into breaking the bonds between the water molecules and not into increasing the average kinetic energy of the molecules. Each gram of water requires a certain amount of energy to change it from liquid to steam without changing its temperature. In fact, this is the same amount of energy that must be released to convert the steam back into liquid water. Furthermore, the temperature at which steam condenses to water is the same as the boiling point. The melting and boiling points for some common substances are given in Table 13-2.

Are You On the Bus?

Q: At the boiling temperature, what determines whether the liquid turns into gas or the gas turns into liquid?

A: If heat is being supplied, the liquid will boil to produce additional gas. However, if heat is being removed, some of the gas will condense to form additional liquid.

Gerald F. Wheeler

The melting of snow and ice in Glacier National Park is a slow process because of the latent heat required to change the ice to liquid water.

A similar change of state occurs when snow melts. The snow does not suddenly become water when the temperature rises to 0°C (32°F). Rather, at that temperature the snow continues to take in energy from the surroundings, slowly changing into water as it does. Incidentally, we are fortunate that it behaves this way; otherwise, we would have gigantic floods the moment the temperature rose above freezing! The latent heat required to melt ice explains why ice can keep a drink near freezing until the last of the ice melts.

On nights when the temperature is predicted to drop below freezing, owners of fruit orchards in California and Florida turn on sprinklers to keep the fruit from freezing. As the water freezes, heat is given off that maintains the temperature of the fruit at 0°C, a temperature above the value at which the fruit freezes. Once the water is completely frozen, the fruit is still protected because ice does not conduct heat very well. The ice serves as a "sweater" for the fruit. However, if the air temperature drops too low, the fruit will be ruined.

Conduction

Thermal energy is transported from one place to another via three mechanisms: conduction, convection, and radiation. Each of these is important in some circumstances and can be ignored in others.

If temperature differences exist within a single isolated object such as a branding iron held in a campfire, thermal energy will flow until thermal equilibrium is achieved. We say that the thermal energy is conducted through the material. **Conduction** takes place via collisions between the particles of the material. The molecules and electrons at the hot end of the branding iron collide with their neighbors, transferring some of their kinetic energy, on the

Figure 13-5 The left end of this ceramic dish is ice-cold while the right end is very hot. This occurs because ceramic is a poor conductor of thermal energy.

Thermal energy is transported along the branding iron by conduction because the brand is hotter than the handle.

average. This increased kinetic energy is passed along the rod via collisions until the end in your hand gets hot.

The rate at which energy is conducted varies from substance to substance. Solids, with their more tightly packed particles, tend to conduct thermal energy better than liquids and gases. The mobility of the electrons within materials also affects the thermal conductivity. Metals such as copper and silver are good thermal **conductors** as well as good electrical conductors. Conversely, electrical insulators such as glass and ceramic are also good thermal **insulators.** A glassblower can hold a glass rod in a flame for a long time without getting burned. The ceramic bowl in Figure 13-5 has regions at drastically different temperatures.

The differences in the conductivity of materials explain why aluminum and wooden benches in a football stadium do not feel the same on a cold day. Before you sit on either bench, they are at the same temperature. When you sit down, some of the thermal energy in your bottom flows into the bench. Because the wooden bench does not conduct the heat well, the spot you are sitting on warms up and feels more comfortable. On the other hand, the aluminum bench continually conducts heat away from your bottom, making your seat feel cold.

The rate at which thermal energy is conducted through a slab of material depends on many physical parameters besides the type of material. You may correctly guess that it depends on the area and thickness of the material. A larger area allows more thermal energy to pass through, and a greater thickness allows less. Experimentation tells us that the difference in the temperatures on the two sides of the slab also matters—the greater the difference, the greater the flow. Table 13-3 gives the thermal conductivities of a variety of common materials.

In our everyday lives, we are more concerned with reducing the transfer of thermal energy than increasing it. We wear clothing to retain our body heat, and we insulate our houses to reduce our heating and air-conditioning bills. Figure 13-6 shows regions of a roof after a snowstorm. The unmelted patches exist where there is better insulation or, in the case of an unheated porch or garage, where there is little or no temperature difference. Table 13-3 allows us

Table 13-3 *Thermal Conductivities for Various Materials*

Material	(W/m · °C)
Solids	
Silver	428
Copper	401
Aluminum	235
Stainless steel	14
Building Materials	
Polyurethane foam	0.024
Fiberglass	0.048
Wood	0.08
Window glass	0.8
Concrete	1.1
Gases	
Air (stationary)	0.026
Helium	0.15

A.A. Bartlett, University of Colorado, Boulder

Figure 13-6 Melting snow patterns reveal differences in thermal conduction. For example, the old garage has been converted to living space, but it appears not to have been insulated.

© Janez Skok/Corbis

Two climbers prepare their gear while sitting in a snow cave on Passo Superior.

to compare the heat loss through slabs of different materials of the same size and thickness for the same difference in temperatures.

Examination of Table 13-3 reveals that static air is a pretty good insulator. This insulating property of air means that porous substances with many small air spaces are good insulators, and it explains why the goose down used in sleeping bags keeps you so warm. It also explains how thermal-knit long underwear keeps you warm. The air trapped in the holes keeps your body heat from being conducted away.

Snow contains a lot of air space between the snowflakes, which makes snow a good thermal insulator. Mountaineers often dig snow caves to escape from severe weather. Likewise, snow-covered ground does not freeze as deep as bare ground.

Are You On the Bus?

Q: Why do people who spend time outdoors in cold weather wear many layers of clothing?

A: In addition to the flexibility of adding and removing layers to get the required insulation, the air spaces between the layers contribute to the overall insulation.

Convection

Thermal energy can also be transferred in fluids by **convection.** In convection the energy is transported by the movement of the fluid. This movement could be forced, as in heating systems or the cooling system in an automobile, or it could happen because of the changes that occur in the density of the fluid when it is heated or cooled. As the gas near the flame of a candle is heated, it becomes less dense and rises because of the buoyant force (Chapter 12).

Convection in Earth's atmosphere plays a fundamental role in our global climate as well as our daily weather. Convection currents arise from the uneven heating of Earth's surface. Glider pilots, hang-glider fliers, and birds of prey (such as hawks and eagles) use convection currents called *thermals* to provide them with the lift they need to keep aloft.

© Royalty-Free/Corbis

Glider pilots search for convective thermals to gain altitude.

Local winds near a large body of water can be caused by temperature differences between the water and the land. The specific heat of water is much greater than that of rock and soil. (Convection currents in the water also moderate the changes in the water temperature.) During the morning, the land warms up faster than the water. The hotter land heats the air over it, causing the air to rise. The result is a pleasant "sea breeze" of cooler air coming from

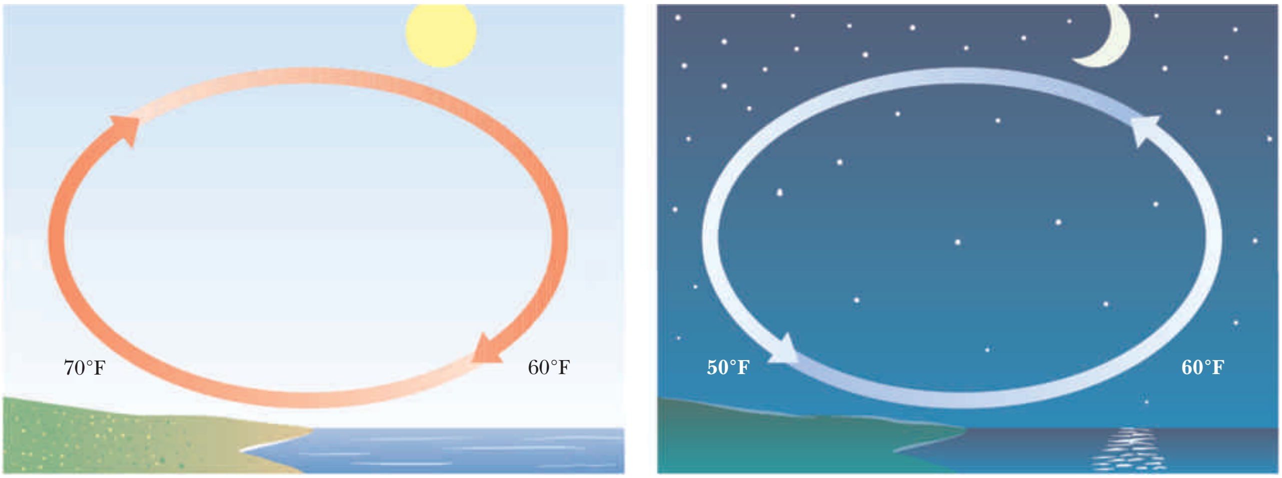


Figure 13-7 The difference in temperature between the land and the water causes breezes to blow (a) onshore during the morning and (b) offshore during the evening.

the water [Figure 13-7(a)]. During the evening, the land cools faster, reversing the convection cycle [Figure 13-7(b)].

Q: What role does convection play in bringing a pot of water to a boil?

A: As the flame or heating element warms the water near the bottom of the pan, it becomes less dense and rises. This circulation causes all of the water to warm up at the same time.

Radiation

The third mechanism for the transfer of thermal energy involves electromagnetic waves. As we will see in Chapter 22, these waves can travel through a vacuum, and thus **radiation** is still effective in situations in which the conduction and convective processes fail. The electromagnetic radiation travels through space and is converted back to thermal energy when it hits other objects. Most of the heat that you feel from a cozy fire is transferred by radiation, especially if the fire is behind glass or in a stove.

All objects emit radiation. Although radiation from objects at room temperature is not visible to the human eye, it can be viewed with special "night glasses" or recorded on infrared-sensitive film. When colors are artificially added, we can distinguish the different temperatures of objects as shown in Figure 13-8.

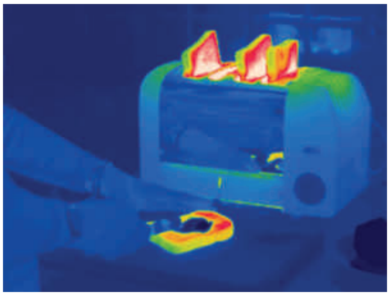


Figure 13-8 This infrared photograph of a toaster shows the different temperatures of its parts.

As the temperature of the object rises, more and more of the radiation becomes visible. Objects such as the heating coils on kitchen stoves glow with a red-orange color. Betelgeuse, the red star marking the right shoulder of the constellation Orion, has a surface temperature of approximately 3000 K. As an object gets hotter, the color shifts to yellow and then white. Our Sun appears white (above Earth's atmosphere) with a temperature of 5800 K. The hottest stars appear blue and have temperatures exceeding 30,000 K.

The radiation that Earth receives from the Sun is typical of an object at 5800 K. If Earth absorbed all of this energy, it would continue to get hotter and hotter until life as we know it could not exist. However, Earth also radiates. Its temperature rises until it radiates as much energy into space as it receives; it reaches equilibrium.

A phenomenon known as the *greenhouse effect* can have a major effect on the equilibrium condition. Visible light easily passes through the windows of a greenhouse or a car, heating the interior. However, the infrared radiation given off by the interior does not readily pass through the glass and is trapped inside. Only when the temperature reaches a high value is equilibrium established. This is one reason why we are warned to never leave children or pets in a car with the windows rolled up on a hot day.

A similar thing happens with Earth. The atmosphere is transparent to visible light, but the water vapor and carbon dioxide in the atmosphere tend to block the infrared radiation from escaping, causing Earth's temperature to increase. The high surface temperatures on Venus are due to the greenhouse effect of its thick atmosphere. It is feared that increases in the carbon dioxide concentration in Earth's atmosphere (due to such things as the burning of fossil fuels) will cause global warming that in turn will cause unwanted changes in Earth's climate. Such alterations in the climate could change the types of crops that will grow and melt the polar ice caps, flooding coastal cities!

Wind Chill

The meteorologist on television announces the temperatures for the day and then adds that it's going to feel even colder because of the wind. If the air is a certain temperature, why does it matter whether the wind is blowing?

Your body is constantly producing heat that must be released to the environment to keep your body from overheating. The primary way that your body gets rid of excess heat is through evaporation. For each liter (about 1 quart) of water that evaporates, roughly 600 kilocalories of heat are absorbed from your body. Although most of us correctly associate this mechanism with sweating, a surprising 25% of the heat lost by evaporation in a resting individual is due to the evaporation of water from the linings of our lungs into the air we exhale. Vigorous activity can produce sweating at a rate in excess of 2 liters per hour, removing 1200 kilocalories per hour, a rate tens of times larger than for a resting individual.

Another form of heat loss is due to convection of air away from the body. Even with no wind, the air leaves your skin on a cold day because its density changes as your body warms the air. A third form of heat loss is radiation loss. If your body is warmer than the surrounding objects such as the walls in a room, your body radiates energy to the walls. This is why you feel cold some mornings even though the air in the room has been heated to normal room temperature. The walls take some time to warm up, and you will continue to radiate to them until they warm up.

The wind near your body greatly alters the effectiveness of these heat transfers. In stationary air, the layer of air next to your skin becomes warm and moist, reducing the further loss of heat to this layer of air. However, if there is a wind, the wind brings new air to your skin that is colder and drier. Warming and adding moisture to this new air requires additional heat from your body.

In the mid-1940s a single index was created—the *windchill factor*—to express the cooling effects for various ambient temperatures and wind speeds in terms of an "equivalent" temperature with no wind. We can use the data shown in Table 13-4 to find the windchill temperature for a thermometer reading of 25°F on a day when the wind is blowing at 40 mph. Look along the top of the table until you locate the 25°F and then move down this column to the row labeled 40 mph along the left-hand side of the table. The entry at the intersection of this row and this column is the equivalent temperature. Therefore, the cooling effects are equivalent to a temperature of 6°F on a calm day.

Table 13-4 *Windchill*

Temperature (°F); Wind (mph)

Calm	40	35	30	25	20	15	10	5	0	−5	−10	−15	−20	−25	−30	−35	−40	−45
5	36	31	25	19	13	7	1	−5	−11	−16	−22	−28	−34	−40	−46	−52	−57	−63
10	34	27	21	15	9	3	−4	−10	−16	−22	−28	−35	−41	−47	−53	−59	−66	−72
15	32	25	19	13	6	0	−7	−13	−19	−26	−32	−39	−45	−51	−58	−64	−71	−77
20	30	24	17	11	4	−2	−9	−15	−22	−29	−35	−42	−48	−55	−61	−68	−74	−81
25	29	23	16	9	3	−4	−11	−17	−24	−31	−37	−44	−51	−58	−64	−71	−78	−84
30	28	22	15	8	1	−5	−12	−19	−26	−33	−39	−46	−53	−60	−67	−73	−80	−87
35	28	21	14	7	0	−7	−14	−21	−27	−34	−41	−48	−55	−62	−69	−76	−82	−89
40	27	20	13	6	−1	−8	−15	−22	−29	−36	−43	−50	−57	−64	−71	−78	−84	−91
45	26	19	12	5	−2	−9	−16	−23	−30	−37	−44	−51	−58	−65	−72	−79	−86	−93
50	26	19	12	4	−3	−10	−17	−24	−31	−38	−45	−52	−60	−67	−74	−81	−88	−95
55	25	18	11	4	−3	−11	−18	−25	−32	−39	−46	−54	−61	−68	−75	−82	−89	−97
60	25	17	10	3	−4	−11	−19	−26	−33	−40	−48	−55	−62	−69	−76	−84	−91	−98

Frostbite times: 30 minutes; 10 minutes; 5 minutes

Table 13-5 *Heat Index*

Relative Humidity (%); Air Temperature (°F)

	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
140	125																				
135	120	128																			
130	117	122	131																		
125	111	116	123	131	141																
120	107	111	116	123	130	139	148														
115	103	107	111	115	120	127	135	143	151												
110	99	102	105	108	112	117	123	130	137	143	150										
105	95	97	100	102	105	109	113	118	123	129	135	142	149								
100	91	93	95	97	99	101	104	107	110	115	120	126	132	138	144						
95	87	88	90	91	93	94	96	98	101	104	107	110	114	119	124	130	136				
90	83	84	85	86	87	88	90	91	93	95	96	98	100	102	106	109	113	117	122		
85	78	79	80	81	82	83	84	85	86	87	88	89	90	91	93	95	97	99	102	105	108
80	73	74	75	76	77	77	78	79	79	80	81	81	82	83	85	86	86	87	88	89	91
75	69	69	70	71	72	72	73	73	74	74	75	75	76	76	77	77	78	78	79	79	80
70	64	64	65	65	66	66	67	67	68	68	69	69	70	70	70	71	71	71	71	71	72

Apparent temperature *is how hot the heat–humidity combination makes it feel.*

Extreme danger; Danger; Extreme caution; Caution

Just as wind can increase the rate at which heat leaves the human body, relative humidity slows the evaporation of perspiration, decreasing the rate. The *heat index* in Table 13-5 combines the effects of temperature and relative humidity to yield an apparent temperature, similar to the windchill factor. Heatstroke is highly likely with continued exposure to heat indexes of 130°F or greater. Sunstroke, heat cramps, and heat exhaustion are likely for heat indexes between 105°F and 130°F, and possible for values between 90°F and 105°F. It should be noted that these values are based on shady, light-wind conditions. Exposure to full sunshine can increase the heat-index values by up to 15°F.

Thermal Expansion

All objects change size as they change temperature. When the temperature increases, nearly all materials expand. But not all materials expand at the same rate. Solids, being most tightly bound, expand the least. All gases expand at

FLAWED REASONING

Susan has just completed sculpting a figurine out of candle wax when she notices that the melting point for the wax is only 125°F. The weather report predicts tomorrow's high temperature to be 100°F with 65% relative humidity, giving an apparent temperature on the heat index of 136°F. **Should Susan store her masterpiece in the refrigerator?**

ANSWER The heat index applies only to humans and other animals that use the sweating process to cool themselves. Susan's statue will not melt.

Edward M. Wheeler

Expansion slots allow bridges to change length with temperature changes without damage.

the same rate, following the ideal gas equation developed in Chapter 11. Each material's characteristic **thermal expansion** is reflected in a number called its *coefficient of expansion*. The coefficient of expansion gives the fractional change in the size of the object per degree change in temperature.

Thermal expansion has many consequences. Civil engineers avoid the possibility of a bridge buckling by including expansion slots and by mounting one end of the bridge on rollers. The gaps between sections of concrete in highways and sidewalks allow the concrete to expand and contract without breaking or buckling. The romantic "clickety-clack" of train rides is due to expansion joints between the rails.

WORKING IT OUT *Thermal Expansion*

Because the coefficient of thermal expansion tells us how much a unit length of material expands as the temperature is raised 1°C, the expansion for a particular object is given by

$$\Delta L = \alpha L \Delta T$$

where ΔL is the change in length, α is the coefficient of thermal expansion, L is the original length, and ΔT is the change in temperature. There is a similar expression for the volume expansion of liquids.

As an example, the coefficient of expansion for steel is 0.000 011 m for each meter of length for each degree Celsius rise in temperature. This means that a bridge that is 50 m long expands by 0.000 55 m, or 0.55 mm, for each degree of temperature increase. If the temperature increases by 40°C from night to day, the bridge expands by 22 mm (almost 1 in.).

We can also obtain this answer using the relationship for thermal expansion:

$$\Delta L = \alpha L \Delta T = \left(\frac{0.000\,011}{°\text{C}}\right)(50 \text{ m})(40°\text{C}) = 0.22 \text{ m}$$

Are You On the Bus?

Q: Why are telephone wires higher in winter than in summer?

A: The wires expand with the hotter temperatures in summer and therefore hang lower.

We use the differences in the thermal expansions of various materials to our advantage. Some thermostats are constructed of two different metal strips bonded together face-to-face, as shown in Figure 13-9. Because the metals have different coefficients of expansion, they expand by different amounts, causing the bimetallic strip to bend. Placing electric contacts in appropriate places allows the thermostat to function as an electric switch to turn a furnace, heater, or air conditioner on and off at specified temperatures.

Are You On the Bus?

Q: How does running hot water on a jar lid loosen it?

A: The metal expands more than the glass, and the lid pulls away from the jar.

Summary

The law of conservation of mechanical energy does not apply whenever frictional effects are present. Often the transformation of mechanical energy to thermal energy is accompanied by temperature changes that produce observable changes in the object. Heat and temperature are not the same thing. Heat is an energy, and temperature is a macroscopic property of the object. The number of calories required to raise the temperature of 1 gram of a substance by 1°C is known as its specific heat.

The first law of thermodynamics tells us that the total change in the internal energy of a system is the sum of the heat added to the system and the work done on the system. This is just a restatement of the law of conservation of energy. Performing 4.2 joules of work on a system is equivalent to adding 1 calorie of thermal energy. Part of this energy increases the average kinetic energy of the atoms; the absolute temperature is directly proportional to this average kinetic energy. Other parts of this energy break the bonds between the molecules and cause substances to change from solids to liquids to gases. At higher temperatures, molecules, atoms, and even nuclei break apart.

There is a limit to how much internal energy can be removed from an object, and thus there is a lowest possible temperature—absolute zero, or −273°C—the same as the zero on the Kelvin scale. A substance at absolute zero has the lowest possible internal energy.

The temperature of a substance does not change while it undergoes a physical change of state. The energy that is released or gained per gram of material is known as the latent heat.

The natural flow of thermal energy is always from hotter objects to colder ones. In the process called conduction, thermal energy is transferred by collisions between particles; in convection the transfer occurs through the movement of the particles; and in radiation the energy is carried by electromagnetic waves.

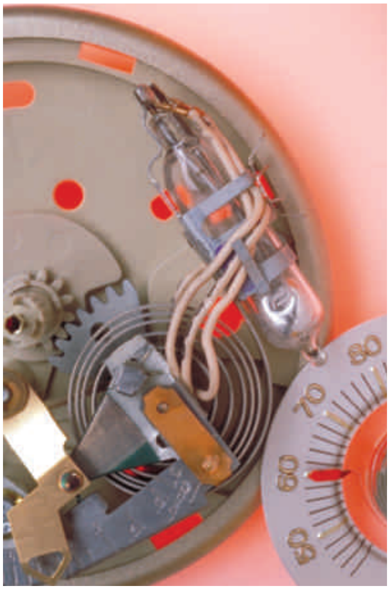


Figure 13-9 A bimetallic strip is used in some thermostats to control furnaces.

Everyday Physics | *Freezing Lakes*

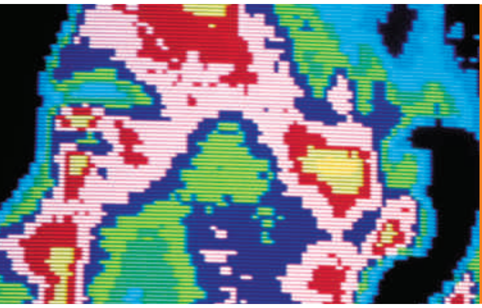
Life as we know it depends on the unique thermal expansion properties of water. All materials change size when their temperatures change. Because density is the ratio of mass to volume and because the mass of an object does not change when heated or cooled, a change in size means a change in the object's density.

As stated in the chapter, most objects expand when heated and contract when cooled. The behavior of water is not so simple. Over most of its liquid range, water behaves as expected, decreasing in volume as its temperature decreases. As the water is cooled below 4°C, however, it expands!

This unusual property affects the way lakes freeze. While cooling toward 4°C, the surface water becomes denser and therefore sinks (Chapter 12), cooling the entire lake. However, once the entire lake becomes 4°C, the surface water expands as it cools further and becomes less dense. Therefore, the cooler water floats on the top and continues to cool until it freezes. Lakes freeze from the top down. However, because ice is a good thermal insulator, most lakes do not freeze to the bottom. If water were like most other materials, the very cold water would sink, and lakes would freeze from the bottom up, creating a challenging evolutionary problem for all aquatic and marine life.

1. What unusual property of water causes ponds and lakes to freeze from the top down?
2. What property of ice keeps lakes from freezing clear to the bottom, even in the coldest of winters?

Because water is denser than ice, the ice floats and covers lakes and ponds in winter. The layer of ice insulates the water below from freezing air temperatures.



CHAPTER 13 *Revisited*

The rate at which an object radiates energy is determined by the difference in temperature between the object and its surroundings, the surface area of the object, and characteristics of the surface. The change in temperature of the object depends primarily on the amount of energy radiated away, the mass of the object, and the specific heat of the material.

Key Terms

absolute zero The lowest possible temperature; 0 K, −273°C, or −459°F.

British thermal unit The amount of heat required to raise the temperature of 1 pound of water by 1°F.

calorie The amount of heat required to raise the temperature of 1 gram of water by 1°C.

change of state The change in a substance between solid and liquid or liquid and gas.

conduction The transfer of thermal energy by the collisions of the atoms or molecules within a substance.

conductor A material that allows the easy flow of thermal energy. Metals are good conductors.

convection The transfer of thermal energy in fluids by means of currents such as the rising of hot air and the sinking of cold air.

heat Energy flowing because of a difference in temperature.

heat capacity The amount of heat required to raise the temperature of an object by 1°C.

insulator A material that is a poor conductor of thermal energy. Wood and stationary air are good thermal insulators.

internal energy The total microscopic energy of an object, which includes its atomic and molecular translational and rotational kinetic energies, its vibrational energy, and the energy stored in the molecular bonds.

latent heat The amount of heat required to melt (or vaporize) 1 gram of a substance. The same amount of heat is released when 1 gram of the same substance freezes (or condenses).

radiation The transport of energy via electromagnetic waves.

specific heat The amount of heat required to raise the temperature of 1 gram of a substance by 1°C.

thermal energy Internal energy.

thermal equilibrium A condition in which there is no net flow of thermal energy between two objects. This occurs when the two objects obtain the same temperature.

thermal expansion The increase in size of a material when heated.

thermodynamics The area of physics that deals with the connections between heat and other forms of energy.

thermodynamics, first law of The increase in the internal energy of a system is equal to the heat added plus the work done on the system.

thermodynamics, third law of Absolute zero may be approached experimentally but can never be reached.

thermodynamics, zeroth law of If objects A and B are each in thermodynamic equilibrium with object C, then A and B are in thermodynamic equilibrium with each other. All three objects are at the same temperature.

Questions and exercises are paired so that most odd-numbered are followed by a similar even-numbered.
Blue-numbered questions and exercises are answered in Appendix B.
indicates more challenging questions and exercises.
WebAssign Many Conceptual Questions and Exercises for this chapter may be assigned online at WebAssign.

Conceptual Questions

1. In an avalanche, the snow and ice begin at rest at the top of the mountain and end up at rest at the bottom. What happens to the gravitational potential energy that is lost in this process?
2. What happens to the sound energy from your stereo speakers?
3. What evidence did Rumford have that heat was not a fluid?
4. Suppose a student was careless in re-creating Joule's experiment and allowed the masses to speed up quickly as they dropped toward the floor. If he equated the change in gravitational potential energy with the change in thermal energy, would he have found 1 calorie to be greater than or less than 4.2 joules? Explain.
5. How are the concepts of work and heat the same? How are they different?

6. What would you expect to find if you measure the temperature of the water at the top and bottom of Niagara Falls? Explain your reasoning.

Cosmo Condina/Stone/Getty

7. It could be argued that the only time you measure the undisturbed temperature of a system is when the reading on the thermometer does not change when it is placed in thermal contact with the system. Use the zeroth law to explain why this is so.

8. Imagine a universe where the zeroth law of thermodynamics was not valid. Would the concept of temperature still make sense in this universe? Why or why not?

9. Could two objects be touching but not be in thermal equilibrium? Explain.

10. Is it possible for a bucket of water in Los Angeles and a bucket of water in New York City to be in thermal equilibrium? Explain.

11. Why is it incorrect to talk about the flow of temperature from a hot object to a colder object?

12. On the inside back cover of this textbook are conversion factors between different units. Why is there no conversion factor between joules and kelvin?

13. What is the difference between heat and temperature?

14. The same amount of heat flows into two different buckets of water, which are initially at the same temperature. Will both buckets necessarily end up at the same temperature? Explain.

15. Patrick claims, "Two buckets of water must have the same heat if they are at the same temperature." Victoria counters, "That's true only if both buckets contain the same amount of water." With which, if either, of these students do you agree? Explain.

16. How do the internal energies of a cup of water and a gallon of water at the same temperature compare?

17. Under what conditions is the first law of thermodynamics valid?

18. Work is done on a system without changing the internal energy of the system. Does heat enter or leave the system during this process? Use the first law of thermodynamics to justify your answer.

19. Does it take more thermal energy to raise the temperature of 5 grams of water or 5 grams of ice by 6°C? Explain.

20. Which of the following does not affect the amount of internal energy of an object: its temperature, the amount of material, its state, the type of material, or its shape?

21. Liquid X and gas Y have identical specific heats. Would 100 calories of heat raise the temperature of 1 liter of liquid X by the same amount as 1 liter of gas Y? Explain your reasoning.

22. One kilogram of material A at 80°C is brought into thermal contact with 1 kilogram of material B at 40°C. When the materials reach thermal equilibrium, the temperature is 68°C. Which material, if either, has the greater specific heat? Explain.

23. A hot block of aluminum is dropped into 500 grams of water at room temperature in a thermally insulated container, where it reaches thermal equilibrium. If 1000 grams of water had been used instead, would the amount of heat transferred to the water be greater than, equal to, or less than it was before? Why?

24. A hot block of iron is dropped into room-temperature water in a thermally insulated container, where it reaches thermal equilibrium. If twice as much water had been used, would the water's temperature change be greater than, equal to, or less than it was before? Why?

25. Why do climates near the coasts tend to be more moderate than those in the middle of the continent?

26. Why does the coldest part of winter occur during late January and February, when the shortest day is near December 21?

27. Given that the melting and freezing temperatures of water are identical, what determines whether a mixture of ice and water will freeze or melt?

28. If you make the mistake of removing ice cubes from the freezer with wet hands, the ice cubes stick to your hands. Why does the water on your hands freeze rather than the ice cubes melt?

© Cengage Learning/ Charles D. Winters

29. Why can an iceberg survive for several weeks floating in seawater that's above freezing?

© Robert Harding/Digital Vision/ Getty Images

30. The boiling point for liquid nitrogen at atmospheric pressure is 77 K. Is the temperature of an open container of liquid nitrogen higher than, lower than, or equal to 77 K? Explain.

31. One hundred grams of ice at 0°C is added to 100 grams of water at 80°C. The system is kept thermally insulated from its environment. Will the equilibrium temperature of the mixture be greater than, equal to, or less than 40°C? Explain your reasoning.

32. An ice cube at 0°C is placed in a foam cup containing 200 grams of water at 60°C. When the system reaches thermal equilibrium, its temperature is 30°C. Was the mass of the ice cube greater than, equal to, or less than 200 grams? Explain your reasoning.

33. Why is steam at 100°C more dangerous than water at 100°C?

34. A new liquid is discovered that has the same boiling point and specific heat as water but a latent heat of vaporization of 10 calories per gram. Assuming that this new liquid is safe to drink, would it be more or less convenient than water for boiling eggs? Why?

35. A system is thermally insulated from its surroundings. Is it possible to do work on the system without changing its internal energy? Is it possible to do work on the system without changing its temperature? Explain.

36. In Washington, D.C., the weather report sometimes states that the temperature is 95°F and the humidity is 95%. Why does the high humidity make it so uncomfortable?

37. Use a microscopic model to explain how a metal rod transports thermal energy from the hot end to the cold end.

38. Why would putting a rug on a tiled bathroom floor make it feel less chilly to bare feet?

39. Rank the following materials in terms of their insulating capabilities: static air, glass, polyurethane foam, and concrete.

40. Which of the following is the best thermal conductor: fiberglass, stainless steel, wood, or silver?

41. If the temperature is 35°F and the wind is blowing at 20 mph, the equivalent windchill temperature is 24°F. Will a glass of water freeze in this situation? Explain your reasoning.

42. You hear on the morning weather report that the outside temperature is −5°F with a windchill equivalent temperature of −40°F. You know that your old car, which is parked outside, will not start if the temperature of the battery drops below −15°F. Will your car start this morning? Why or why not?

43. The respective thermal conductivities of iron and stainless steel are 79 W/m · °C and 14 W/m · °C. Use these data to explain why you need to use potholders for pots with iron handles but not for pots with stainless steel handles.

44. Why might a cook put large aluminum nails in potatoes before baking them?

45. In northern climates drivers often encounter signs that read, "BRIDGE FREEZES BEFORE ROADWAY." Why does this occur?

46. You have just made yourself a hot cup of coffee and are about to add the cream, which is at room temperature. Suddenly the phone rings and you have to leave the room for a while. Is it better to add the cream to the coffee before you leave or after you get back if you want your coffee as hot as possible? Why?

47. When pilots fly under clouds, they often experience a downdraft. Why is this?

Richard Hamilton Smith/ Dembinsky Photo Assoc.

48. It is midafternoon and you are canoeing down a river that empties into a large lake. You are having a hard time making progress because of a stiff wind in your face. Is this situation likely to get better or worse at sunset? Explain.

49. A black car and a white car are parked next to each other on a sunny day. The surface of the black car gets much hotter than the surface of the white car. Which mode of energy transport is responsible for this difference?

50. Earth satellites orbit Earth in a very good vacuum. Would you expect these satellites to cool off when they enter Earth's shadow? Explain.

51. A Thermos bottle is usually constructed from two nested glass containers with a vacuum between them, as shown in the following figure. The walls are usually silvered as well. How does this construction minimize the loss of thermal energy?

52. Will a Thermos bottle (shown in the preceding figure) keep something cold as well as it keeps it hot? Explain.

53. The metal roof on a wooden shed makes noises when a cloud passes in front of the Sun. Why?

54. Why might a glass dish taken from the oven and put into cold water shatter?

55. Suppose the column in an alcohol-in-glass thermometer is not uniform. How would the spacing between the degrees on a wide portion of the thermometer compare with those on a narrow portion?

56. When a mercury thermometer is first put into hot water, the level of the mercury drops slightly before it begins to climb. Why?

Exercises

57. How much heat is required to raise the temperature of 500 g of water from 20°C to 30°C?

58. If the temperature of 600 g of water drops by 8°C, how much heat is released?

59. How much work is required to push a crate with a force of 200 N across a floor a distance of 4 m? How many calories of thermal energy does the friction produce?

60. How many joules of gravitational potential energy are converted to kinetic energy when 100 g of lead shot falls from a height of 50 cm? How many calories are released to the surroundings if none of this kinetic energy is converted to other forms when the shot hits the floor?

61. A physics student foolishly wants to lose weight by drinking cold water. If he drinks 1 L (1000 cm^3) of water at 10°C below body temperature, how many Calories will it take to warm the water?

62. A typical jogger burns up food energy at the rate of about 40 kJ per minute. How long would it take to run off a piece of cake if it contains 400 Calories?

63. During a process, 28 J of heat are transferred into a system, while the system itself does 12 J of work. What is the change in the internal energy of the system?

64. What is the change in the internal energy of a system if 15 J of work are done on the system and 6 J of heat are removed from the system?

65. When an ideal gas was compressed, its internal energy increased by 180 J and it gave off 150 J of heat. How much work was done on this gas?

66. If the internal energy of an ideal gas increases by 150 J when 240 J of work is done to compress it, how much heat is released?

67. It takes 250 cal to raise the temperature of a metallic ring from 20°C to 30°C. If the ring has a mass of 90 g, what is the specific heat of the metal?

68. If it takes 3400 cal to raise the temperature of a 500-g statue by 44°C, what is the specific heat of the material used to make the statue?

69. How many calories will it take to raise the temperature of a 50-g gold chain from 20°C to 100°C?

70. How many calories would it take to raise the temperature of a 300-g aluminum pan from 293 K to 373 K?

71. Six grams of liquid X at 35°C are added to 3 grams of liquid Y at 20°C. The specific heat of liquid X is 2 cal/g · °C, and the specific heat of liquid Y is 1 cal/g · °C. If each gram of liquid X gives up 2 cal to liquid Y, find the change in temperature of each liquid.

72. In Exercise 71, imagine that liquid X continues to transfer energy to the other liquid 12 calories at a time. How many transfers would be required to reach a common temperature? What is this equilibrium temperature?

73. Eighty grams of water at 70°C is mixed with an equal amount of water at 30°C in a completely insulated container. The final temperature of the water is 50°C.

   a. How much heat is lost by the hot water?
   b. How much heat is gained by the cold water?
   c. What happens to the total amount of internal energy of the system?

74. If 200 g of water at 100°C is mixed with 300 g of water at 50°C in a completely insulated container, what is the final equilibrium temperature?

75. A kettle containing 3 kg of water has just reached its boiling point. How much energy, in joules, is required to boil the kettle dry?

76. How much heat would it take to melt a 1-kg block of ice?

77. You wish to melt a 3-kg block of aluminum, which is initially at 20°C. How much energy, in joules, is required to heat the block to its melting point of 660°C? How much energy, in joules, is required to melt the aluminum without changing its temperature?

78. How much heat is required to convert 400 g of ice at −5°C to water at 5°C? (*Hint:* review Exercise 77.)

79. What is the change in length of a metal rod with an original length of 2 m, a coefficient of thermal expansion of 0.00002/°C, and a temperature change of 20°C?

80. A steel railroad rail is 24.4 m long. How much does it expand during a day when the low temperature is 50°F (18°C) and the high temperature is 91°F (33°C)?

14

Available Energy

▶The energy of the hot water and steam from a geyser can be used to run engines, yet the internal energy of a pail of room-temperature water, although quite high, isn't as useful as an energy source. Why is this true, and what would it take to extract this internal energy and make it available for performing useful work?

(See page 296 for the answer to this question.)

Old Faithful Geyser in Yellowstone National Park, Wyoming. Hot water from geysers can be used as an energy source.

MECHANICAL energy can be completely converted into the internal energy of an object. This is clearly demonstrated every time an object comes to rest because of frictional forces. In the building of a scientific world view, the belief in a symmetry often leads to interesting new insights. In this case it seems natural to ask whether the process can be reversed. Is it possible to recover this internal energy and get some mechanical energy back? The answer is yes, but it is not an unqualified yes.

Imagine that we try to run Joule's paddle-wheel experiment (Figure 14-1) backward. Suppose we start with hot water and wait for the weight to rise up from the floor. Clearly, we don't expect this to happen. The water can be heated to increase its internal energy, but the hot water will not rotate the paddle wheel. Water can be very hot and thus contain a lot of internal energy, but mechanical work does not spontaneously appear.

The first law of thermodynamics doesn't exclude this; it places no restrictions on which energy transformations are possible. As long as the internal energy equals or exceeds that needed to raise the weight, there would be no violation of the first law if some of the internal energy were used to do this. And yet it doesn't happen. The energy is there, but it is not available. Apparently the availability of energy depends on the form that it takes.

This aspect of nature, unaccounted for so far in the development of our world view, is addressed in the second law of thermodynamics. It's a subtle law that has a rich history, resulting in three different statements of the law. The first form deals with heat engines.

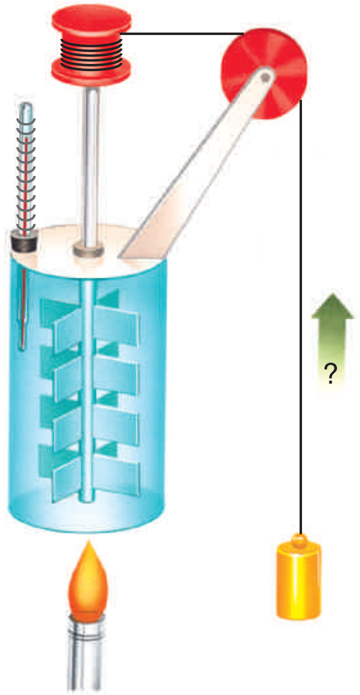


Figure 14-1 Why won't the weight rise when we heat the water?

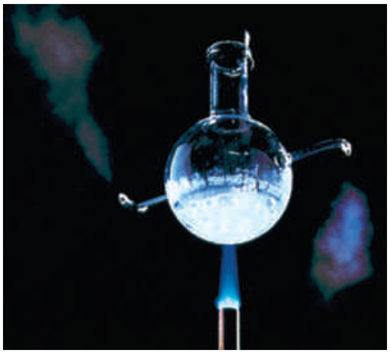
Heat Engines

We can extract some of an object's internal energy under certain circumstances. Internal energy naturally flows from a higher-temperature region to one of lower temperature. A hot cup of coffee left on your desk cools off as some of its thermal energy flows to the surroundings. The coffee continues to cool until it reaches thermal equilibrium with the room. Energy flows out of the hot region because of the presence of the cold one. But no work—no mechanical energy—results from this flow.

Many schemes have been proposed for taking part of the heat and converting it to useful work. Any device that does this is called a **heat engine**. The simplest and earliest heat engine is traced back to Hero of Alexandria. About AD 50, Hero invented a device similar to that shown in Figure 14-2. Heating the water-filled container changes the water into steam. The steam, escaping through the two tubes, causes the container to rotate. From our modern perspective, we may judge this to be more of a toy than a machine. The importance of this device, however, was that mechanical energy was in fact obtained—the container rotated. Apparently, Hero did do something useful with his heat engine; there are stories that he used pulleys and ropes to open a temple door during a religious service. (Probably much to the shock of the worshippers!)

The Industrial Revolution began with the move away from animal power toward machine power. The first heat machines were used to pump water out of mines in England. Waste coal was cheap at the pithead, and the engines were inefficient. By the 1790s James Watt had developed steam engines that were more thermally efficient and were increasingly used in applications requiring powerful and reliable energy sources, such as water systems, mills, and forges.

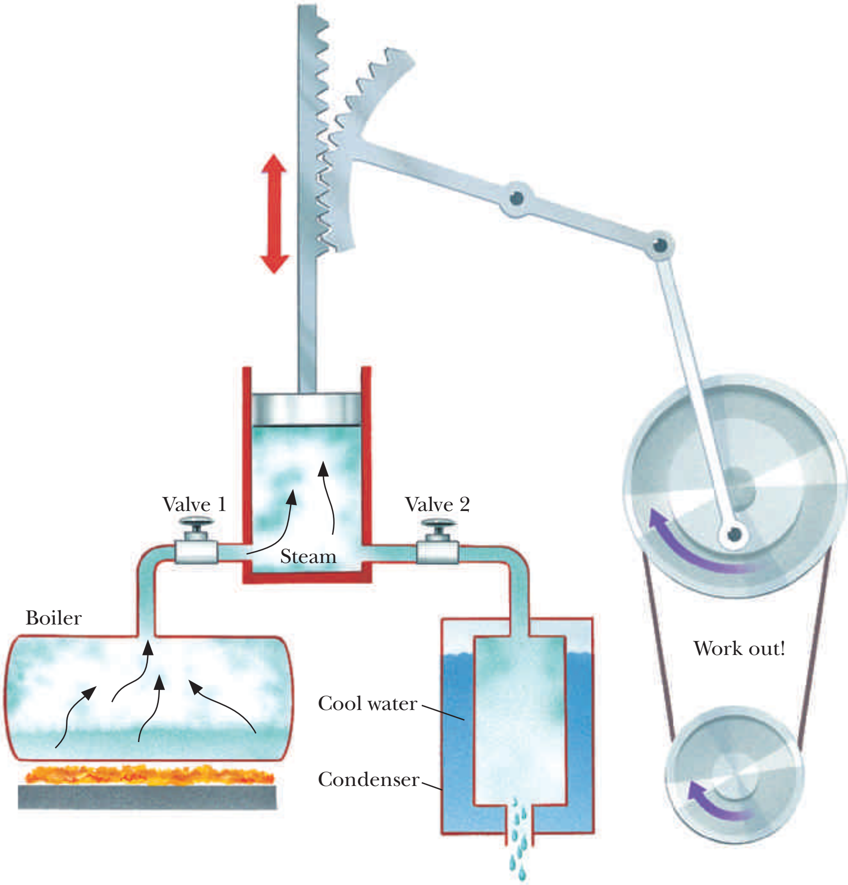
Figure 14-3 shows the essential features of the most successful of the early steam engines. Invented by Watt in 1769, it had a movable piston in a cylinder. The flow of heat was not a result of direct thermal contact between objects but of the transfer of steam that was heated by the hot region and cooled by the



Courtesy of VWR Corporation

Figure 14-2 A modern version of Hero's heat engine rotates under the action of the escaping steam.

Figure 14-3 The essential features of Watt's steam engine. Opening valve 1 lets steam into the chamber, raising the piston. Closing valve 1 and opening valve 2 reduces the pressure, allowing the piston to fall.



The steam locomotive is a heat engine.

Image not available due to copyright restrictions

cold region. Alternately heating and cooling the steam in the cylinder drove the piston up and down, producing mechanical work.

The opening of the American West was helped by another heat engine: "the iron horse," or steam locomotive. A more modern heat engine is the internal combustion engine used in automobiles. Replacing the wood and steam, gasoline explodes to produce the high-temperature gas. The explosions move pistons, allowing the engine to extract some of this energy to run the automobile. The remaining hot gases are exhausted to the cooler environment.

Although there are many types of heat engines, all can be represented by the same schematic diagram. To envision this, recall that all heat engines involve the flow of energy from a hotter region to a cooler one. Figure 14-4(a) shows how we represent this flow. A heat engine is a device placed in the path of this flow to extract mechanical energy. Figure 14-4(b) shows heat flowing from the hotter region; part of this heat is converted to mechanical work, and the remainder is exhausted to the colder region. You can verify that heat is thrown away by an automobile's engine by putting your hand near (but not directly on) the exhaust pipe. The exhausted gases are hotter than the surrounding air. Without the cool region, the flow would stop, and no energy would be extracted.

Are You On the Bus?

Q: How much work does a heat engine perform if it extracts 100 joules of energy from a hot region and exhausts 60 joules to a cold region?

A: Conservation of energy requires that the work be equal to 40 joules, the difference between the input and the output.

Ideal Heat Engines

The first law of thermodynamics requires that the sum of the mechanical work and the exhausted heat be equal to the heat extracted from the hot region. But exhausted heat means wasted energy. When engines were developed at the beginning of the Industrial Revolution, engineers asked, "What kind of engine will get the maximum amount of work from a given amount of heat?"

In 1824 French army engineer Sadi Carnot published the answer to this question. Carnot found the best possible engine by imagining the whole process as a thought experiment. He assumed that his engine would use idealized gases and there would be no frictional losses due to parts rubbing against each other. His results were surprising. Even under these ideal conditions, the heat engine must exhaust some heat.

Carnot's work led to one version of the **second law of thermodynamics** and an understanding of why internal energy cannot be completely converted to mechanical energy. That is, even the best theoretical heat engine cannot convert 100% of the incoming heat into work.

◀ heat-engine form of the second law of thermodynamics

It is impossible to build a heat engine to perform mechanical work that does not exhaust heat to the surroundings.

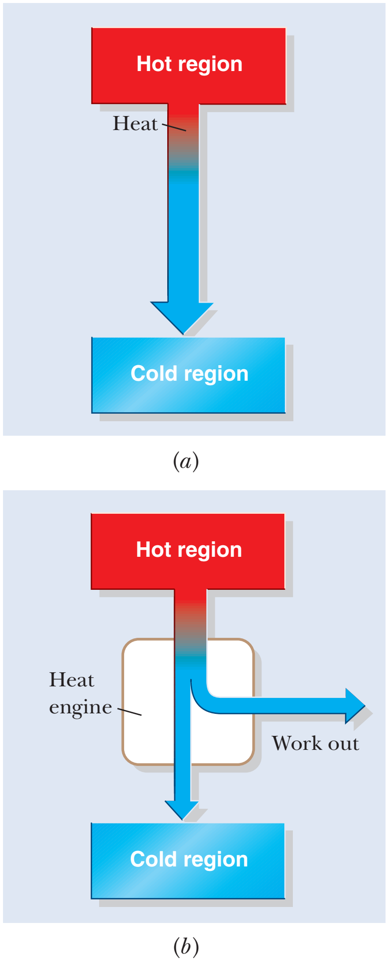


Figure 14-4 (a) A schematic showing the natural flow of thermal energy from a higher-temperature region to a lower-temperature region. (b) The white square represents the many types of heat engine. The heat engine converts part of the heat from the hot region to mechanical work and exhausts the remaining heat to the cold region.

Stated slightly differently, the fact that the engine must throw away heat means that no heat engine can run between regions at the same temperature. This is unfortunate, because it would be a boon to civilization if we could "reach in" and extract some internal energy from a single region. For example, think of all the energy that would be available in the oceans. If we could build a single-temperature heat engine, it could be used to run an ocean liner. Its engine could take in ocean water at the front of the ship, extract some of the water's internal energy, and drop ice cubes off the back, as shown in Figure 14-5. Notice that this hypothetical engine isn't intended to get something for nothing; it only tries to get out what is there. But the second law says that this is impossible.

Perpetual-Motion Machines

Since the beginning of the Industrial Revolution, inventors and tinkerers have tried to devise a machine that would run forever. This search was fueled by the desire to get something for nothing. A machine that did some task without requiring energy would have countless applications in society, not to mention the benefits that would accrue to its inventor. No such machine has ever been invented; in fact, the only "successful" perpetual-motion machines have been devices that were later shown to be hoaxes.

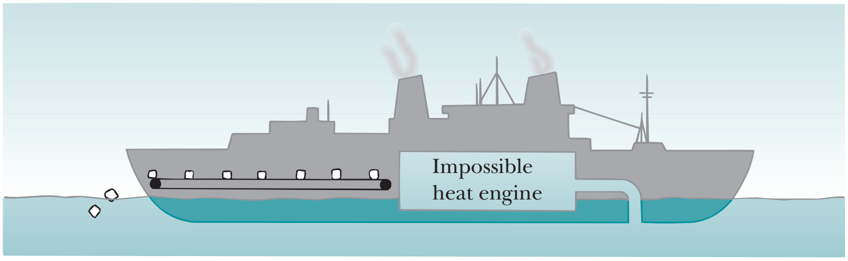


Figure 14-5 An impossible engine in an ocean liner extracts energy from ocean water, makes ice cubes, and propels the ship.

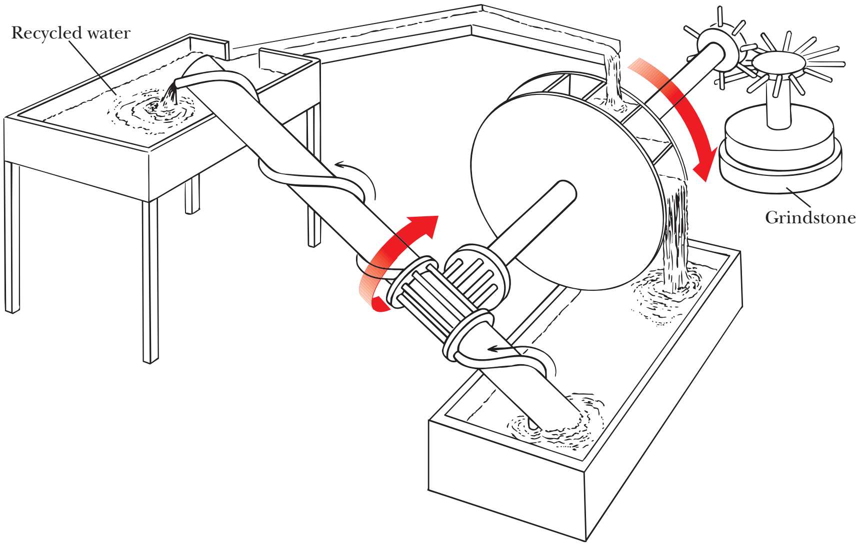


Figure 14-6 Fludd's proposed perpetual-motion machine cannot work because it would violate the first law of thermodynamics.

In the 17th century, English physician Robert Fludd proposed the device shown in Figure 14-6. Fludd wanted to turn the waterwheel to move the millstone and at the same time return the water to the upper level. It didn't work. Machines like Fludd's violate the first law of thermodynamics by trying to get more energy out of a device than is put into it. Every machine is cyclic by definition. After doing something the machine returns to its original state to start the whole process over again. Fludd's scheme was to have the machine start with a certain amount of energy (the potential energy of the water on the upper level), do some work, and then return to its original state. But if it did some work, some energy was spent. Returning the machine to its original state would require getting something for nothing, a violation of the first law.

Other perpetual-motion machines have been less ambitious. They were simply supposed to run forever without extracting any useful output. They also didn't work. Even if we ask nothing of such a machine except to run—and thus stay within the confines of the first law of thermodynamics—it still will not run forever. These machines failed because they were attempting to violate the second law of thermodynamics.

To illustrate this, suppose we invent such a machine as a thought experiment. Figure 14-7 is a diagram of one possibility. A certain amount of energy is initially put into the system, and somehow, the system is started. The paddle wheel turns in the water and, as the Joule experiment showed us, produces an increase in the temperature of the water. Mechanical energy has been converted to internal energy, as indicated by the water's temperature rise. Thermal energy from the hot water flows to the pad below the water. The pad is a heat engine designed to capture this energy and convert it to mechanical energy. The mechanical energy, in turn, is used to drive gears that rotate the paddles.

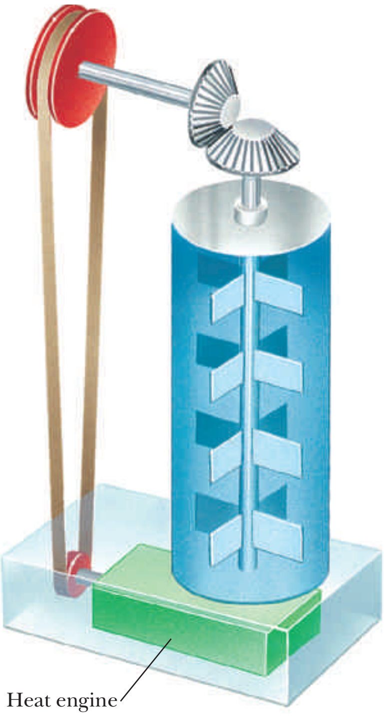


Figure 14-7 This proposed perpetual-motion machine would violate the second law of thermodynamics.

Does the machine continue to run? Notice that this is a perfect machine, and we can assume that there are no frictional losses; so if it fails, it does so because of some fundamental reason. Such engines have been built—and they have all failed. The problem lies with the heat engine in the pad. Any heat engine, no matter how good, returns less mechanical energy than the thermal energy it receives. Therefore, our machine runs down, and we have failed. We do not fail because we try to create energy but because we cannot use the energy that we have. Once the energy is converted to internal energy, it is no longer fully available.

Even in a simpler machine without a heat engine, there would still be moving parts. Any rubbing of moving parts increases the machine's internal energy. All this internal energy would have to be converted back into mechanical energy if the machine were to run forever. The second law tells us that this cannot happen.

All machines and heat engines, no matter how complicated, cannot avoid the constraints imposed by the first and second laws of thermodynamics.

FLAWED REASONING

A classmate claims to suddenly understand the second law of thermodynamics. He explains, "All machines necessarily have moving parts that experience friction. This is why a heat engine can never transform its entire heat input into work." **Do you think your classmate understands the second law?**

ANSWER Your classmate seems to understand the first law of thermodynamics (energy conservation) but is missing the key point of the second law. The second law of thermodynamics states that even in the absence of any friction, it is still impossible to transform thermal energy entirely into mechanical energy. Some of the input energy must be exhausted.

Real Engines

Extended presentation available in the *Problem Solving* supplement

All engines can be rated according to their efficiencies. In general, efficiency can be defined as the ratio of the output to the input. In the case of heat engines, the **efficiency** η of an engine is equal to the ratio of the work W produced divided by the heat Q extracted from the hot region:

$$\eta = \frac{W}{Q}$$

efficiency $= \dfrac{\text{work out}}{\text{heat in}}$

Carnot's ideal heat engine has the maximum theoretical efficiency. This efficiency can be expressed as a simple relationship using Kelvin temperatures:

$$\eta = 1 - \frac{T_c}{T_h}$$

efficiency of an ideal heat engine

The Carnot efficiency depends only on the temperatures of the two regions. It is larger (that is, closer to 1) if the temperature of the exhaust region T_c is low or that of the hot region T_h is high. The largest efficiency occurs when the temperatures are as far apart as possible. Usually, this efficiency is multiplied by 100 so that it can be stated as a percentage. Real engines produce more waste heat than Carnot's ideal engine, but his relationship is still important because it sets an upper limit for the efficiencies of real engines.

Today, steam engines are used primarily to drive electric generators in power plants. Although these engines are certainly not Carnot engines, their efficiencies can be increased by making their input temperatures as high as possible and their exhaust temperatures as low as possible. Because of constraints imposed by the properties of the materials used in their construction, these engines cannot be run much hotter than 550°C. Exhaust temperatures cannot be much lower than about 50°C. Given these constraints, we can calculate the maximum theoretical efficiency of the steam engines used in electricity-

A coal-fired electricity-generating plant.

Cooling towers at the nuclear power generating facility on Three Mile Island near Harrisburg, Pennsylvania.

generating plants. Remembering to convert the temperatures from Celsius to Kelvin, we have

$$\eta = 1 - \frac{T_c}{T_h} = 1 - \frac{323\ \text{K}}{823\ \text{K}} = 0.61 = 61\%$$

Actual steam engines have efficiencies closer to 50%. Besides the efficiency of the engine, we must consider the efficiency of the boiler for converting the chemical energy of the fuel into heat. Typical oil- or coal-fired power plants have overall efficiencies of about 40% or less. Nuclear power plants use uranium as a fuel to make steam. Safety regulations require that they run at lower temperatures, so they are 5–8% less efficient than the oil- or coal-fired plants. In other words, nuclear plants exhaust more waste heat for each unit of electricity generated.

Q: What is the maximum theoretical efficiency for a heat engine running between 127°C and 27°C?

A: Being careful to convert these temperatures to the Kelvin scale, we have

$$\eta = 1 - \frac{T_c}{T_h} = 1 - \frac{300\ \text{K}}{400\ \text{K}} = 1 - 0.75 = 0.25 = 25\%$$

Not all engines are heat engines. Those that don't go through a thermodynamic process are not heat engines and can have efficiencies closer to 100%. Electric motors are close to being 100% efficient if you look only at the electric motor. However, the overall efficiency of the electric motor must include the energy costs of generating the electricity and the energy losses that occur in the electric transmission lines. Because most electricity is produced by steam engines, the overall efficiency is quite low.

WORKING IT OUT *Efficiency*

An engine operates with an efficiency of 20%. If the engine has a power output of 15 kW (i.e., does 15,000 J of work each second), how many joules does the engine exhaust each second to the cold region?

The efficiency is defined as the ratio of useful work to the heat extracted from the hot region:

$$\eta = \frac{W}{Q_h}$$

An efficiency of 20% means that only 20% of the extracted heat is converted to useful work and the rest is exhausted to the cold region. For every joule of work done, 4 J of heat are exhausted. If 15,000 J of work are done each second, then 60,000 J of heat are exhausted.

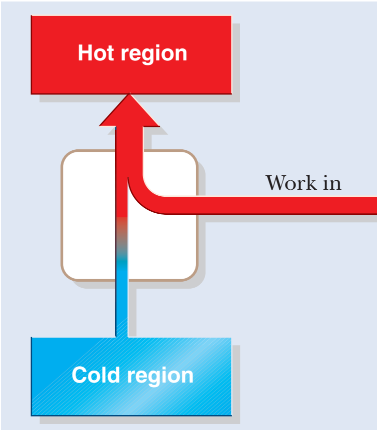


Figure 14-8 A refrigerator uses mechanical work to transfer heat from a colder region to a hotter one.

Refrigerators

There are devices that extract heat from a cooler region and deposit it into a hotter one. These are essentially heat engines running backward. **Refrigerators** and air conditioners are common examples of such devices. By reversing the directions of the arrows in Figure 14-4(b), we produce the schematic of the process shown in Figure 14-8.

Refrigerators move heat in a direction opposite to its natural flow. The inside of your refrigerator is the cold region, and your room is the hot region. The refrigerator removes heat from the inside and exhausts it to the warm region outside. If you put your hand by the base of the refrigerator, you can feel the heat being transferred to the kitchen. Similarly, if you walk by the external part of an air conditioner, you feel heat being expelled outside the house. In both cases the warm region gets hotter, and the cool gets colder.

The icebox of olden days was a simple device: place a block of ice on the top shelf and your produce on the bottom shelf. The modern refrigerator is almost as simple. It is constructed from the four basic parts illustrated in Figure 14-9. The *evaporator* (1) is a long metal tube that allows the low-pressure, cold liquid refrigerant to have thermal contact with the air inside the refrigerator. When a liquid evaporates, it absorbs heat from its surroundings. A refrigerant, such as Freon-12, is often used because it evaporates at a low temperature (–29°C). The *compressor* (2) pressurizes the gas, and the resulting high-pressure gas passes through the *condenser* (3), a second long metal tube outside the refrigerator. Thermal energy is released into the kitchen as the gas condenses back into a liquid. The liquid cools as it passes through the *expansion valve* (4), and the process repeats.

Refrigerators require work to move energy from a lower-temperature region to a higher-temperature region. Therefore, the heat delivered to the higher-temperature region is larger than that extracted from the lower-temperature region. The extra heat is the amount of work done on the system. In fact, this process leads to an equivalent statement of the second law of thermodynamics.

refrigerator form of the second law of thermodynamics

It is impossible to build a refrigerator that can transfer heat from a lower-temperature region to a higher-temperature region without using mechanical work.

A **heat pump** is used in some homes to both cool during the summer and heat in the winter. It is simply a reversible heat engine. In the summer the heat pump functions as an air conditioner by extracting heat from inside your house. In the winter it runs in reverse (like a refrigerator), extracting energy from the outside air and putting it into your house.

It may seem strange to be able to extract heat from the cold air. Remember that heat and temperature are not the same. Even on the coldest days, the outside air still has enormous amounts of internal energy. The heat pump transfers some of this internal energy from outside to inside. Actually, there is an economical limit. If the outside temperature is too low, it takes more energy to run the heat pump than it does to use electric baseboard heaters. This situation can be corrected if a warmer region such as underground water is available as a source of the internal energy.

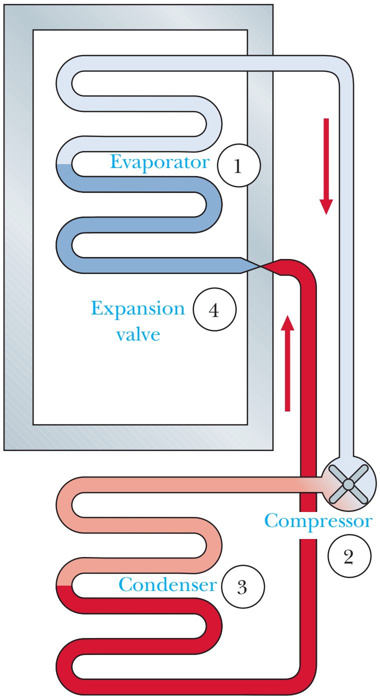


Figure 14-9 A schematic for a refrigerator.

Order and Disorder

Whether it is a heat engine or a refrigerator, the second law of thermodynamics essentially says that we can't break even. If we are trying to get mechanical

Q: How much energy does an air conditioner exhaust if it requires 200 joules of mechanical work to extract 1000 joules of energy from a house?

A: Conservation of energy requires that the exhaust equal 1200 joules, the sum of the inputs.

Courtesy of Marc Sherman

Heat pumps can be used to cool houses in summer and heat them in winter. They can extract energy from the outside air even in cold weather.

© Cengage Learning/David Rogers

A new deck of cards has a high degree of order.

energy from a thermal source, we have to throw some heat away. If we want to cool something, we have to do work to counteract the natural flow of energy. But these two forms of the second law offer little insight into why this is so. The reason lies in the microscopic behavior of the many-particle systems that make up matter. To understand the second law of thermodynamics, we need to look at the details of such systems.

We begin by looking at systems in general. Any system consists of a collection of parts. Assuming that these parts can be shifted around, the system has a number of possible arrangements. We will examine systems and determine their organization because, as we will see, it is their organizational properties that lie at the heart of the second law. An organizational property can be such a thing as the position of objects in a box or the height of people in a community.

Suppose your system is a new deck of playing cards. The cards are arranged according to suits and within suits according to value. The organizational property in this case is the position of the card within the deck. If somebody handed you a card, you would have no trouble deciding where it came from. If the deck were arranged by suit but the values within the suits were mixed, you would not be able to pinpoint the location of the card, but you could say from which fourth of the deck it came. In a completely shuffled deck, you would have no way of knowing the origin of the card. The first arrangement is very organized, the second less so, and the last one very disorganized. We call a system that is highly organized an **ordered system** and one that shows no organization a **disordered system.**

Another way of looking at the amount of organization is to ask how many equivalent arrangements are possible in each of these situations. When the deck is arranged by suit and value, there is only one arrangement. When the values are shuffled within suits, there are literally billions of ways the cards could be arranged within each suit. When we completely shuffle the deck, the number of possible arrangements becomes astronomically large (8×10^{67}). The more disordered system is the one with the larger number of equivalent arrangements.

A simple system of three coins on a tray can model microscopic order. An obvious organizational property of this system is the number of heads (or tails) facing up. How many different arrangements are there? If the coins are different, there are eight different arrangements for the three coins, as shown in Figure 14-10.

In real situations the macroscopic property—for example, the total energy—doesn't depend on the actual properties of a particular atom. To apply our coin analogy to this situation, we would examine the different arrangements without identifying individual coins. In other words, we should simply count the number of heads and tails. How many different arrangements are there now? Four. Of the eight original arrangements, two groups of three are now indistinguishable, as shown in Figure 14-11. Each of these groups has three *equivalent states*. The arrangements with all heads or all tails occur in only one way and thus have only one state each. Arrangements with only one state have the highest order. The arrangements that occur in three ways have the lowest order.

HHH
THH
HTH
HHT
HTT
THT
TTH
TTT

Figure 14-10 The eight possible arrangements of three different coins.

Are You On the Bus?

Q: How many different arrangements can you make with three colored blocks: one *r*ed, one *b*lue, and one *g*reen?

A: The arrangements are *rbg, rgb, bgr, brg, grb,* and *gbr*. Therefore, there are six possible arrangements.

Understanding the microscopic form of the second law of thermodynamics depends on realizing that the order of real systems is constantly changing. This dynamic nature of systems occurs because macroscopic objects are composed of an immense number of atomic particles that are continually moving and therefore changing the order of the system. We can use our coins to understand this.

To model the passage of time, we shake the tray to flip the three coins. If we repeatedly start our system with a particular high-order arrangement, we observe that after one flip, the amount of order in the system usually decreases. Each of the eight states has an equal probability of occurring. However, the probability of a low-order arrangement occurring is not equal to that of a high-order arrangement, simply because there are more low-order possibilities. Of the eight possible states, only two yield high-order arrangements. The chance is only 2 in 8, or 25%, of obtaining a high-order arrangement. The other 75% of the time we expect to obtain two heads and a tail or two tails and a head.

If we increase the number of coins, the probabilities change. With four coins, for example, the number of possible states grows to 16. Adding one additional coin doubles the total number of combinations because we are adding a head or a tail to each of the previous combinations. But again, there are only two arrangements with the highest order, those having all heads or all tails. The probability now of obtaining a high-order arrangement is 2 in 16, or about 12%. As the number of elements in the system increases, the probability of obtaining a high-order arrangement gets smaller. Conversely, the probability of obtaining a low-order arrangement increases with the size of the system.

For example, if we have 8 coins, the probability of obtaining the highest-order distribution (all heads or all tails) is less than 1%. If we increase the number of coins to 21, we only have one chance in a million of getting all heads or all tails. If the number of coins increases to that of the number of air molecules in a typical bedroom (10^{27}), the probability decreases to 1 in 10^{82}.

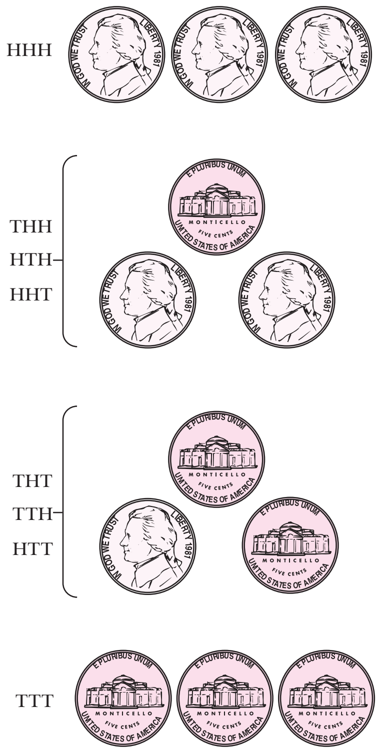


Figure 14-11 The four possible arrangements of three indistinguishable coins.

Are You On the Bus?

Q: What is the probability of obtaining all heads or all tails with five coins?

A: Adding the additional coin doubles the total number of possible combinations to 32. Therefore, we have 2 chances out of 32, or 6%, of obtaining all tails or all heads.

As another example, let's consider the air molecules in your room. Presumably, any air molecule can be anywhere in the room. A high-order arrangement may have all the molecules in one small location; a low-order arrangement would have them spread uniformly throughout the available space in one of many equivalent states. The number of low-order arrangements is astronomically higher than the number of high-order ones.

Entropy

We now introduce a new concept, called **entropy**, as a measure of a system's organization. A system that has some recognizable order has low entropy—the more disorganized the system, the higher its entropy. As with gravitational potential energy, we are concerned only with changes in entropy; the actual numerical value of the entropy does not matter.

WORKING IT OUT *Probability*

Suppose you had three dice: one red, one blue, and one green. If you roll all three dice at the same time, what is the probability that the sum of the dice will be 12? We expect the probability to be low. You certainly would not want to bet your house that you could do it on the first roll. But how improbable is it?

There are six possible values for each die, so there are $6 \times 6 \times 6 = 216$ states, or possible ways for the three dice to roll. We need to find all of the states that add up to 12. Suppose that the red die rolls a 1. The blue and the green dice would have to add up to 11. That yields two possible states: 1 5 6 and 1 6 5. There are no other ways to roll a sum of 12 if the red die is only 1. We next let the red die roll 2, and find all the possible ways to get a total of 12. We find through this process a total of 25 different states that yield a total of 12:

1 5 6	2 4 6	3 3 6
1 6 5	2 5 5	3 4 5
	2 6 4	3 5 4
		3 6 3
4 2 6	5 1 6	6 1 5
4 3 5	5 2 5	6 2 4
4 4 4	5 3 4	6 3 3
4 5 3	5 4 3	6 4 2
4 6 2	5 5 2	6 5 1
	5 6 1	

There are 25 possible ways, out of 216 total, to roll a sum of 12 with three dice. The probability of rolling a 12 is therefore $\frac{25}{216} = 0.116 = 11.6\%$. Don't bet your house on it!

FLAWED REASONING

Sandra is explaining a get-rich-quick scheme to her friend Marie.

Sandra: "I have been flipping this nickel and the last 19 flips have all been heads! We should take this nickel to Las Vegas and bet someone that the next flip will be tails. We can't lose! The chance of a nickel landing heads 20 times in a row is less than one in a million."

Marie: "Let's stay home. If that nickel is not rigged, then any toss is as likely to give tails as heads. You would only have a 50% chance of winning your bet, even if the last 19 tosses turned up heads."

Should they go to Vegas?

ANSWER Marie is right. The results of past tosses of the nickel do not affect the next toss. Unless the nickel is weighted, every toss has an equal probability of being heads or tails. It's amazing that Sandra was able to get heads 19 times in a row. The odds against that are nearly 500,000 to 1.

We argued in the last section that the order of a system of many particles tends to decrease with time. Therefore, the entropy of the system tends to increase. This tendency is expressed by another version of the second law of thermodynamics.

entropy form of the second law of thermodynamics ▶

The entropy of an isolated system tends to increase.

The word *tends* needs to be stressed. There is nothing that says the entropy *must* increase. It happens because of the overwhelming odds in its favor. It is still *possible* for all the air molecules to be in one corner of your room. (That would leave you gasping for air if you weren't in that corner!) Nothing prohibits this from happening. Fortunately, the likelihood of this actually happening is vanishingly small.

This entropy version looks so different from the forms of the second law developed for heat engines and refrigerators that you may think that they are different laws. The connection between them is that the motion associated with internal energy has a low-order arrangement, whereas macroscopic motion requires a high degree of organization. Atomic motions are random; at any instant, particles are moving in many directions with a wide range of speeds. If we could take a series of snapshots of these particles and scramble the snapshots, we could not distinguish them; one snapshot is just like another. There appears to be no order to the motions or positions of the particles.

The macroscopic motion of an object, on the other hand, gives organization to the motions of the object's atoms. Although the particles are randomly moving in all directions on the atomic level, they also have the macroscopic motion of the object. All the atoms in a ball falling with a certain kinetic energy are essentially moving in the same direction (Figure 14-12). When the ball strikes the ground, the energy is not lost; the collective motions are randomized. The atoms move in all directions with equal likelihood.

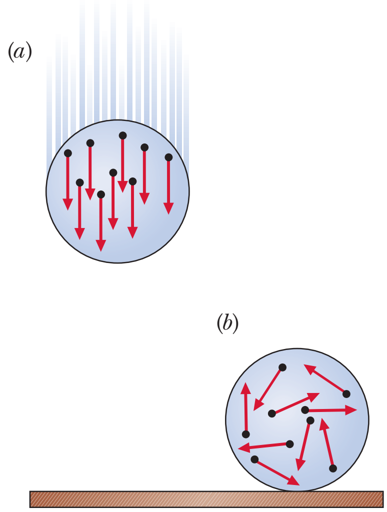


Figure 14-12 **(a) The motions of atoms in a falling ball have a high degree of order. (b) The motions after the ball hits the ground are random with a low degree of order.**

Although it is certainly physically possible for all the particles to once again move in a single direction at some future time (without somebody picking it up), it is so unlikely that we never expect to see it happen. If it did happen, however, some of the internal energy of the ball's particles would then be available to do some mechanical work. This would be bizarre; at some moment, a ball initially at rest would suddenly fly off with some kinetic energy.

Decreasing Entropy

Although the overall entropy of a system tends to increase, isolated pockets of activity can show a decrease in entropy—that is, an increase in order. But these increases in order are paid for with an overall decrease in the order of the universe. Life, for example, is a glorious example of increasing order. It begins as a simple fertilized egg and evolves into a complicated human being. Clearly, order is increasing. But this increase is accomplished through the use of energy. To bring about the increase in human order, a great deal of energy becomes less available for performing useful work. The order of the environment decreases accordingly.

As a simpler example, imagine that you have two buckets of water, one hot and the other cold. If you place a heat engine between the buckets, you can do some work. After the heat engine operates for a while, the buckets reach the same temperature. The system now has a higher entropy. You can decrease the entropy by heating one bucket and cooling the other. But you can only do this by increasing the entropy of the universe. We saw this with refrigerators. You can make the hot region hotter and the cold region colder but only after mechanical work is put in. That use of work lowers the availability of the energy in the universe to do mechanical work.

Entropy and Our Energy Crisis

Save energy! That is the battle cry these days. But why do we have to *save* energy? According to the first law of thermodynamics, energy is neither created nor destroyed. The total amount of energy is constant. There is no need

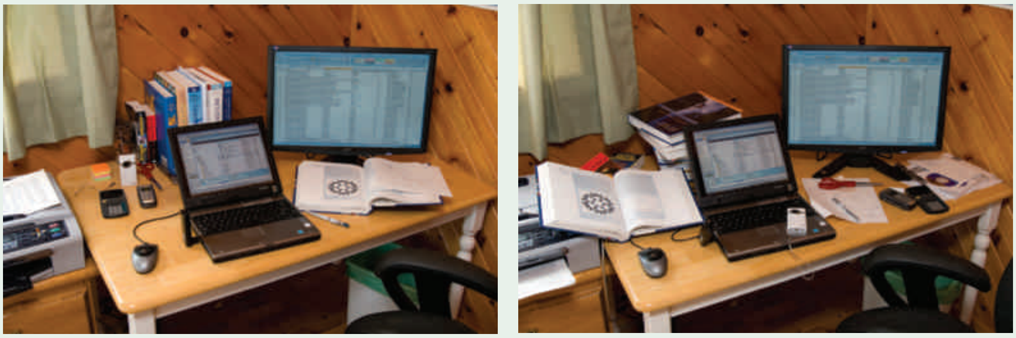
Everyday Physics | *Arrow of Time*

The concept of entropy gives insight into the character of time. Imagine a motion picture of a soccer game played backward. It looks silly because the order of the events doesn't match our experiences. There is a direction to time. But why do things happen in a particular sequence? According to most of the laws of nature we have established, other sequences of events *could* happen: The parabolic curve of the thrown football is the same regardless of which direction the film is played. Yet the game—played backward—is unreal. Even a repeating, cyclic event like a child on a swing has clues telling you whether the movie is running forward or backward. If the child ceases pumping, the swinging dies down because of frictional effects. Left without an input of energy, everyday motions stop when the macroscopic energy gets transformed into internal energy.

In principle, a stationary pendulum bob could transfer some of its internal energy into swinging the bob. This would (simply) require that the bob's atoms all move in the same direction at the same time. They are all moving but in random directions. It could happen that at some time they could all be moving in the same direction. It could happen, but it doesn't. The entropy form of the second law of thermodynamics tells us why: all systems tend toward disorder. This fact of nature gives a direction to time.

The direction of time is implicit in many events. Bright new paint has a radiant color because of the particular molecules and their particular arrangement. As time passes, there is a mixing of the molecules with the air and a rearranging of the molecules in the paint—and the paint fades. Structures crumble; their original shapes are very ordered, but as time passes, they deteriorate. Order is lost. The culprit is chance, and the consequence is increasing entropy. Time has a direction because the universe has a natural tendency toward disorder.

1. Which law of thermodynamics allows us to define a direction to time?
2. Why do you not violate the second law of thermodynamics when you clean your room?



A desk work area is an example of a system that tends toward disorder.

to conserve energy; it happens naturally. The crux of the matter is really the second law. There are pockets of energy in our environment that are more valuable than others. Given the proper conditions, we can use this energy to do some useful work for society. But if we later add up all the energy, we still have the same amount. The energy used to drive our cars around town is transformed via frictional interactions and exhaust, the consumption of food results in our body temperatures being maintained as well as moving us around, and so on. All the energy is present and accounted for.

Water naturally flows downhill. The water is still there at the bottom of the hill, but it is less useful. If all the water is at the same level, there is no further flow. Similarly, if all the energy in the universe is spread out uniformly, we can get no more "flow" from one pocket to another.

The real energy issue is the preservation of the valuable pockets of energy. We can burn a barrel of oil only once. When we burn it, the energy becomes less useful for doing work, and the entropy of the universe goes up. The second law doesn't tell us how fast entropy should increase. It does not tell us how fast we must use up our pockets of energy; it only says that it will occur. The decision of finding an acceptable rate is left to us. The battle cry for the future should be, "Slow down the increase in entropy!"

Everyday Physics | *Quality of Energy*

With the exceptions of a geothermal source of hot water heating a home or a windmill pumping water out of a well, most energy that we use in our lives has been converted from its original form to the form we use. An obvious example is the electrical energy that lights our homes. This energy often comes from a fossil fuel that is burned to heat water to form steam, which turns a generator to produce the electricity that lights our homes.

It is not possible to convert, or even transfer, energy without "losing" some of the energy in the process. (By *losing energy* we mean that some of the energy is transformed to some form other than the one desired.) Even charging a battery—storing energy for later use—requires more energy than gets stored in the battery. A more obvious loss is that due to frictional forces. If we use a waterwheel to turn an electric generator, some of the input energy is transformed to thermal energy by the frictional forces in the rubbing of the mechanical parts. Losses also occur when electrical energy is transported from one place to another. A final loss comes from the thermal bottleneck described by the second law of thermodynamics. Whenever we convert thermal energy to *any* other form of energy, the second law of thermodynamics tells us that we always lose some energy to other forms: It is impossible to make the conversion with 100% efficiency.

Gas water heaters are more efficient than electric ones.

All conversions of energy are not equivalent. Some energy conversions are less efficient and thus more costly to our world's energy budget. To obtain an accurate measure of the efficiency of the energy you use, you need to go back to the original source and calculate the overall efficiency of delivering it to your home and its final use. Suppose, for example, that the initial conversion is 50% efficient. For every unit of energy you start with, you have to give up one-half unit. If the process of transporting the energy to your home is also 50% efficient, the amount that you get to use is one-half of one-half, or one-fourth, of the original. To calculate the total efficiency, you multiply the fractional efficiencies of each stage together.

The table shows the relative efficiencies of two methods of heating water in your home. The efficiency of each step is shown as well as the overall efficiency through that step. Notice that the lowest efficiency occurs during the generation of electricity in the coal-fired plant. The extra steps of making and transporting the electricity reduce the efficiency of electric heat by a factor of $2\frac{1}{2}$ compared to heating with natural gas. Therefore, the quality of natural gas for heating is much higher than that of electricity produced from coal.

1. Heating household water with natural gas is only 64% efficient, while heating it with electricity is 92% efficient. Why is it better to use gas?
2. Give an example of energy lost as it is transformed from one form to another.

Efficiency for Heating Water

	Step Efficiency (%)	Accumulative Efficiency (%)
Electric		
Mining of coal	96	96
Transportation of coal	97	96
Generation of electricity	33	31
Electrical transmission	85	26
Heating	92	24
Gas		
Production of natural gas	96	96
Transportation	97	93
Heating	64	60

Summary

Mechanical energy can be completely converted into internal energy, but it is not possible to recover all this internal energy and get the same amount of mechanical energy back. The energy is there, but it is not available.

We can extract some of an object's internal energy using a heat engine. Part of the heat is converted to mechanical work, and the remainder is emitted as exhaust. The first law of thermodynamics requires that the sum of the mechanical work and the exhaust heat be equal to the heat extracted. The second law of thermodynamics says that we cannot build a heat engine without an exhaust. As a consequence, it is impossible to completely convert heat to mechanical energy.

People have tried to construct two kinds of perpetual-motion machines. The first kind violates the first law of thermodynamics by trying to get more energy out of a device than is put into it. The perpetual-motion machines of the second kind do not try to do any useful work but just try to run forever. They fail because they violate the second law of thermodynamics.

The efficiency of an ideal heat engine—a Carnot engine—depends on the temperatures of the input heat source and the exhaust region. The maximum theoretical efficiency increases as the difference in these two temperatures increases and is given by $\eta = 1 - T_c/T_h$, where T_h is the input temperature and T_c is the exhaust temperature in kelvin. The efficiencies of real engines are always less than this.

Refrigerators and air conditioners are essentially heat engines running backward. These devices require work to move energy from a lower-temperature region to a higher-temperature region. An equivalent form of the second law says that we cannot build a refrigerator that moves energy from a colder region to a hotter region without work being done.

The third form of the second law says that the entropy of an isolated system tends to increase. Entropy is a measure of the order of a system. Entropy increases as the order within a system decreases. The entropy of a system can decrease, but the decrease is paid for with an overall increase in the entropy of the universe. Life is an example of decreasing entropy (increasing order).

Our energy crisis is really related to the using up of the pockets of energy in our environment that are more valuable than others. We still have the same amount of energy as we've always had.

CHAPTER 14 *Revisited*

Performing useful work with the internal energy in an object requires that the energy be able to flow from the object to a region at a lower temperature. Regardless of the amount of internal energy in an object, if there is no colder region nearby, the energy is useless for running an engine. On the other hand, the colder the exhaust region, the larger is the fraction of the internal energy that can be used.

Key Terms

disordered system A system with an arrangement equivalent to many other possible arrangements.

efficiency The ratio of the work produced to the energy input. For an ideal heat engine, the Carnot efficiency is given by $1 - T_c/T_h$.

entropy A measure of the order of a system. The second law of thermodynamics states that the entropy of an isolated system tends to increase.

heat engine A device for converting heat into mechanical work.

heat pump A reversible heat engine that acts as a furnace in winter and an air conditioner in summer.

ordered system A system with an arrangement belonging to a group with the smallest number (possibly one) of equivalent arrangements.

refrigerator A heat engine running backward.

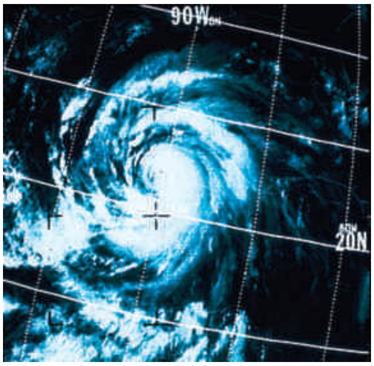
thermodynamics, second law of There are three equivalent forms: (1) It is impossible to build a heat engine to perform mechanical work that does not exhaust heat to the surroundings. (2) It is impossible to build a refrigerator that can transfer heat from a lower-temperature region to a higher-temperature region without using mechanical work. (3) The entropy of an isolated system tends to increase.

Blue-numbered answered in Appendix B = more challenging questions

Questions and exercises are paired so that most odd-numbered are followed by a similar even-numbered.
Blue-numbered questions and exercises are answered in Appendix B.
indicates more challenging questions and exercises.
WebAssign **Many Conceptual Questions and Exercises for this chapter may be assigned online at WebAssign.**

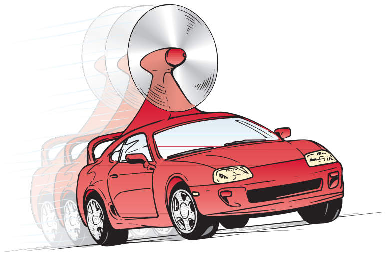
Conceptual Questions

1. What does a heat engine do?
2. In a heat engine, 140 joules of energy are extracted from a hot region. According to the first law of thermodynamics, what is the maximum amount of work that can be done by this engine? Is this result consistent with the second law of thermodynamics? Explain.
3. Why is it not possible to run an ocean liner by taking in seawater at the bow of the ship, extracting internal energy from the water, and dropping ice cubes off the stern?
4. One possible end to the universe is for it to reach thermal equilibrium; that is, it would have a uniform temperature. Would this temperature be absolute zero? Explain.
5. In an ideal heat engine, 1000 joules of energy are extracted from the hot region at 800 K. One of the laws of thermodynamics requires that if the cold region is at 320 K, the engine must exhaust 400 joules of energy. Which law of thermodynamics requires this?
6. If the ideal heat engine used in Question 5 must exhaust 400 joules of energy, one of the laws of thermodynamics indicates that the engine can do no more than 600 joules of useful work. Which law of thermodynamics indicates this?
7. Does the following statement agree with the second law of thermodynamics? “No engine can transform its entire heat input into work.”
8. Would it be possible to design a heat engine that produces no thermal pollution? Explain.
9. It is possible to float heat engines on the ocean and extract some of the internal energy of the water by extending a tube well beneath the ocean’s surface. Why is it necessary for the heat engine to have this tube in order to satisfy the second law of thermodynamics?
10. A hurricane can be thought of as a heat engine that converts thermal energy from the ocean to the mechanical motion of its winds. Use this idea to explain why the wind speeds decrease as the hurricane moves away from the equator.



U.S. Environmental Science Services Administration

11. Many people have tried to build perpetual-motion machines. What restrictions does the first law of thermodynamics place on the possibility of building a perpetual-motion machine?
12. What restrictions does the second law of thermodynamics place on the possibility of building a perpetual-motion machine?
13. Explain how the following simplified statements of the first and second laws of thermodynamics are consistent with the versions given in this chapter. First: You cannot get ahead. Second: You cannot even break even.
14. A student proposes to run an automobile without using any fuel by building a windmill on top of the car. The car’s motion will cause the windmill to rotate and generate electricity. The electricity will run a motor, maintaining the car’s motion, which in turn causes the windmill to rotate. What, if anything, is wrong with this proposal?



15. What does it mean to say that the human body is a heat engine with an efficiency of 20%?
16. Why are nuclear power plants less efficient than coal-fired plants?
17. What happens to the efficiency of an ideal heat engine as its input temperature is increased while its exhaust temperature is held fixed?
18. If the input temperature of an ideal heat engine is fixed, what happens to its efficiency as its exhaust temperature is increased?
19. Heat engine A operates between 300°C and 20°C, whereas heat engine B operates between 300°C and 80°C. Which engine has the greater possible theoretical efficiency? Explain.
20. You are building a heat engine in which the temperature difference between the hot and cold regions is 100 K. Will it be more efficient to have your cold region as cold as possible or as hot as possible? Why?
21. An engineer claims that she could build a more efficient automobile engine if the materials science division could develop piston materials that could withstand higher operating temperatures. Why would this help?

22. A car company has just designed an ultra-fuel-efficient car, and they wish to advertise the best possible miles per gallon. If the engine can be thought of as a heat engine with a constant operating temperature, would it be better to run the trial on a hot day or a cold day? Why?

23. How is the following statement equivalent to the heat-engine form of the second law of thermodynamics? "The efficiency of a heat engine must be less than 1."

24. With his paddle-wheel apparatus, Joule determined that 4.2 joules of mechanical work are equivalent to 1 calorie of heat. Imagine that he had mistakenly used a heat engine instead and had measured the heat flowing into the engine and the work done by the engine to determine the conversion factor. Would this have produced a conversion factor for 1 calorie that was greater than, equal to, or less than 4.2 joules? Why?

25. You are installing a central air-conditioning system in which the main unit sits outside your home. For maximum cooling, should you locate the unit on the sunny or the shady side of the house? Why?

26. Bob moves into a new home that is heated with an electric heat pump. He decides that because no heat pump can be perfectly efficient, he will disconnect the heat pump and use the electricity to run a baseboard heater instead. Will Bob's energy bill increase, remain the same, or decrease? Why?

27. Would it be possible to keep a room cool by leaving the door of the refrigerator open? Why or why not?

28. An air-conditioner mechanic is testing a unit by running it on the workbench in an isolated room. What happens to the temperature of the room?

29. A salesperson tries to sell you a "new and improved" air conditioner that does not need a window opening. The unit just sits in the corner of the room and keeps it cool. Use the second law of thermodynamics to convince the salesperson that this will not work.

30. Imagine you are heating your home with a heat pump that uses a small amount of work to transfer heat from the cold outside air to the warm inside air. Your friend suggests that you set up a second heat engine using the air inside the house as the hot region and the outside air as the cold region to provide the necessary work to drive the heat pump. Which law or laws of thermodynamics does this money-saving scheme violate?

31. State the refrigerator form of the second law of thermodynamics in your own words.

32. Give an example that clearly illustrates the meaning of the refrigerator form of the second law of thermodynamics.

33. In what way is the following statement equivalent to the refrigerator form of the second law of thermodynamics? "The natural direction for the flow of heat is from hotter objects to colder objects."

34. Is the following statement equivalent to the refrigerator form of the second law of thermodynamics? "In moving energy from a cold region to a hot region, the energy delivered to the hot region must be the sum of the work performed plus the energy extracted from the cold region." Explain your reasoning.

35. The coefficient of performance for a refrigerator is defined as the ratio of the heat extracted from the colder system to the work required. Will this number be greater than, equal to, or less than 1 for a good refrigerator? Explain.

36. Why is the efficiency of a heat engine always less than 1, whereas the coefficient of performance for a heat pump is not so constrained?

37. You have two friends who always play the state lottery. Janice's strategy is to always select last week's winning number for this week's draw. In contrast, Jeremy has researched the winning number combinations for the last ten years and always selects a combination that has not yet won. Which strategy, if either, is more likely to be a winner? Explain.

38. You watch a friend flipping coins and notice that heads has come up four times in a row. Does this mean that it is more likely that tails will come up on the next throw? Explain.

39. What sums of two dice have the highest and lowest order?

40. What sums of three dice have the highest order?

41. Why does the sum of two dice equal 7 more often than any other number?

42. Your friend challenges that, given 25 chances to roll two dice, you cannot roll a sum of 7 at least three times. Should you accept the challenge? Why or why not?

43. Why do "boxcars" (a pair of sixes) occur so rarely when throwing two dice?

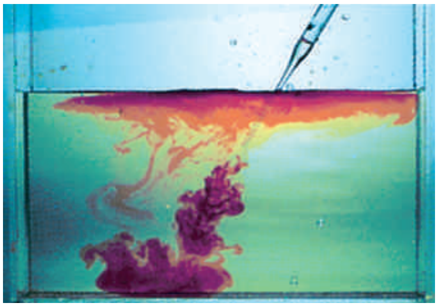
44. On average, how many times would you expect to roll "boxcars" (a pair of sixes) with two dice if you rolled the dice a total of 180 times?

45. State the entropy form of the second law of thermodynamics in your own words.

46. Give an example that clearly illustrates the meaning of the entropy form of the second law of thermodynamics.

47. One end of a steel bar is held over a flame until it is red hot. We know from Chapter 13 that when the bar is removed from the flame, the thermal energy will diffuse along the bar until the entire bar has the same equilibrium temperature. Use a microscopic model to explain why the bar's entropy (that is, its disorder) is increasing during this equilibration process.

48. What happens to the entropy of the universe as the orange liquid diffuses into the clear liquid?



49. What happens to the entropy of the universe as an ice cube melts in water? Explain.

50. A cold piece of metal is dropped into an insulated container of hot water. After the system has reached an equilibrium temperature, has the entropy of the universe increased or decreased? Explain.

51. Describe a system in which the entropy is decreasing. Is this system isolated from its surroundings?

52. What happens to the entropy of a human as it grows from childhood to adulthood? Is this consistent with the second law of thermodynamics? Explain.


Russell Streadbeck (both)

53. When water freezes to ice, does the order of the water molecules increase or decrease? What does this imply about the change in entropy in the rest of the universe?

54. A ringing bell is inserted into a large glass of water. The bell and the water are initially at the same temperature and are insulated from their surroundings. Eventually, the bell stops vibrating, and the water comes to rest.
   a. What happens to the mechanical energy of the bell?
   b. What happens to the temperature of the system?
   c. What happens to the entropy of the system?

55. If you slide a crate across the floor, kinetic energy is converted to thermal energy as it comes to rest. Why will adding thermal energy to a stationary crate not cause it to move?

56. Are Mexican jumping beans a violation of the second law of thermodynamics? Explain.

57. Imagine that you could film the motion of the gas molecules in the room. Would you be able to tell whether the film was running forward or backward? Would it make a difference if air were being released from a balloon? Explain.

58. You have an aquarium with a divider down the middle. One side is filled with hot water, and the other is filled with cold water. Imagine that as the divider is removed you can film the individual collisions between water molecules. When watching the film, how could you tell whether it was running forward or backward?

59. Which of the following statements explains why we are currently experiencing a worldwide energy crisis?
   a. The amount of energy in the world is decreasing rapidly.
   b. The entropy of the world is increasing rapidly.
   c. The entropy of the world is decreasing rapidly.

60. How does slowing the increase in entropy help solve the world's energy crisis?

61. Which results in the larger increase in the entropy of the universe: heating a liter of room-temperature water to boiling using natural gas or using electricity? Why?

62. Why is heating water on a gas stove more efficient than heating it on an electric stove?

63. It is the middle of winter, and you live in a house with electric baseboard heating. Your friend chides you for being wasteful for turning on the oven to 400°F for 45 minutes just to cook a single baked potato. How do you respond?

64. Since childhood we've been told to turn out the lights when we leave a room. Does this really reduce the electric bill during the winter for a house with electric heating? Why?

Exercises

65. What input energy is required if an engine performs 300 kJ of work and exhausts 400 kJ of heat?

66. How much work is performed by a heat engine that takes in 2000 J of heat and exhausts 800 J?

67. An engine takes in 9000 cal of heat and exhausts 4000 cal of heat each minute it is running. How much work does the engine perform each minute?

68. A heat engine requires an input of 10 kJ per minute to produce 3 kJ of work per minute. How much heat must the engine exhaust per minute?

69. What is the efficiency of a heat engine that does 50 J of work for every 200 J of heat it takes in?

70. An engine exhausts 1200 J of energy for every 3600 J of energy it takes in. What is its efficiency?

71. An engine has an efficiency of 40%. How much energy must be extracted to do 900 J of work?

72. An engine operates with an efficiency of 25%. If the engine does 600 J of work every minute, how many joules per minute are exhausted to the cold region?

73. An engine takes in 600 cal and exhausts 450 cal each second it is running. How much work does the engine perform each minute? What is the engine's efficiency?

74. How much work does an engine produce each second if it takes in 8000 cal and exhausts 5000 cal each second? What is the efficiency of the engine?

75. An engineer has designed a machine to produce electricity by using the difference in the temperature of ocean water at different depths. If the surface temperature is 20°C and the temperature at 50 m below the surface is 12°C, what is the maximum efficiency of this machine?

76. A heat engine takes in 1000 J of energy at 1000 K and exhausts 600 J at 500 K. What are the actual and maximum theoretical efficiencies of this heat engine?

77. An ideal heat engine has a theoretical efficiency of 60% and an exhaust temperature of 27°C. What is its input temperature?

78. What is the exhaust temperature of an ideal heat engine that has an efficiency of 50% and an input temperature of 400°C?

79. How much work is required by a refrigerator that takes in 1000 J from the cold region and exhausts 1500 J to the hot region?

80. A refrigerator uses 600 J of work to remove 2400 J of heat from a room. How much heat does it exhaust?

81. How much work per second (power) is required by a refrigerator that takes 700 J of thermal energy from a cold region each second and exhausts 1500 J to a hot region?

82. A heat pump requires 500 W of electrical power to deliver heat to your house at a rate of 2400 J per second. How many joules of energy are extracted from the cold air outside each second?

83. The coefficient of performance for a heat pump is defined as the ratio of the heat extracted from the colder system to the work required. If a heat pump requires an input of 400 W of electrical energy and has a coefficient of performance of 3, how much energy is delivered to the inside of the house each second?

84. If a refrigerator requires an input of 200 J of electrical energy each second and has a coefficient of performance of 5, how much heat energy is extracted from the refrigerator each second?

85. Show that four coins can be arranged in 16 different ways.

86. Show that the combination of four coins with the lowest order (two heads and two tails) is the one with the largest number of arrangements.

87. What is the probability of rolling a total of 6 with two dice?

88. What is the probability of rolling a sum of 10 with two dice?

89. The total number of possible states for three dice is $6 \times 6 \times 6 = 216$. What is the probability of throwing a sum equal to 5?

90. The total number of possible states for three dice is $6 \times 6 \times 6 = 216$. What is the probability of throwing a sum equal to 15?

The Big Picture

Waves—Something Else That Moves

Imagine standing near a busy highway trying to get the attention of a friend on the other side. How could you signal your friend? You might try shouting first. You could throw something across the highway, you could make a loud noise by banging two rocks together, you could shine a flashlight at your friend, and so on.

Signals can be sent by one of two methods. One method includes ways in which material moves from you to your friend—such as throwing a pebble. The other method includes ways in which energy moves across the highway without any accompanying material. This second method represents phenomena that we usually call waves.

The study of waves has greatly expanded the physics world view. Surprisingly, however, waves do not have a strong position in our commonsense world view. It's not that wave phenomena are uncommon, but rather that many times the wave nature of the phenomena is not recognized. Plucking a guitar string, for example, doesn't usually invoke images of waves traveling up and down the string. But that is what happens. The buzzing of a bee probably does not generate thoughts of waves either. We will discover interesting examples of waves in unexpected situations.

Raymond Gendreau/Stone/Getty

Sculling on Lake Powell creates interesting wave patterns.

Waves are certainly common enough—we grow up playing with water waves and listening to sound waves—but most of us do not have a good intuitive understanding of the behavior of waves. Ask yourself a few questions about waves: Do they bounce off materials? When two waves meet, do they crash like billiard balls? Is it meaningful to speak of the speed of a wave? When speaking of material objects, the answers to such questions seem obvious, but when speaking of waves, the answers require closer examination.

We study waves for two reasons. First, because they are there; studying waves adds to our understanding of how the world works. The second reason is less obvious. As we delve deeper and deeper into the workings of the world, we reach limits beyond which we cannot observe phenomena directly. Even the best imaginable magnifying instrument is too weak to allow direct observation of the subatomic worlds. Our search to understand these worlds yields evidence only by indirect methods. We must use our common experiences to model a world we cannot see. In many cases the modeling process can be reduced to asking whether the phenomenon acts like a wave or acts like a particle.

To answer the question of whether something acts like a wave or a particle, we must expand our commonsense world view to include waves. After you study such common waves as sound waves, we hope you will be ready to "hear" the harmony of the subatomic world.

It's not that wave phenomena are uncommon, but rather that many times the wave nature of the phenomena is not recognized.

15

Vibrations and Waves

▶Water drops falling onto the surface of water produce waves that move outward as expanding rings. But what is moving outward? Does the wave disturbance carry energy or momentum? What happens when two waves meet? How does wave motion differ from particle motion?

(See page 323 for the answer to this question.)

Don Bonsey/Stone/Getty

Circular waves are formed by falling water drops.

If you stretch or compress a spring and let go, it vibrates. If you pull a pendulum off to one side and let it go, it oscillates back and forth. Such vibrations and oscillations are common motions in our everyday world. If these vibrations and oscillations affect surrounding objects or matter, a wave is often generated. Ripples on a pond, musical sounds, laser light, exploding stars, and even electrons all display some aspects of wave behavior.

Waves are responsible for many of our everyday experiences. Fortunately, nature has been kind; all waves have many of the same characteristics. Once you understand one type, you will know a great deal about the others.

We begin our study with simple vibrations and oscillations. We then examine common waves, such as waves on a rope, water waves, and sound waves, and later progress to more exotic examples, such as radio, television, light, and even "matter" waves.

▷ Extended presentation available in the *Problem Solving* supplement

Simple Vibrations

If you distort an object and release it, elastic forces restore the object to its original shape. In returning to its original shape, however, the inertia of the displaced portion of the object causes it to overshoot, creating a distortion in the opposite direction. Again, restoring forces attempt to return the object to its original shape and, again, the object overshoots. This back-and-forth motion is what we commonly call a **vibration,** or an **oscillation.** For all practical purposes, the labels are interchangeable.

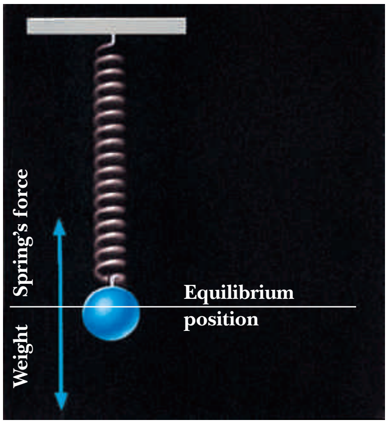


Figure 15-1 At the equilibrium position, the upward force due to the spring is equal to the weight of the mass.

A mass hanging on the end of a vertical spring exhibits a simple vibrational motion. Initially, the mass stretches the spring so that it hangs at the position where its weight is just balanced by the upward force of the spring, as shown in Figure 15-1. This position—called the **equilibrium position**—is analogous to the undistorted shape of an object. If you pull downward (or push upward) on the mass, you feel a force in the opposite direction. The size of this restoring force increases with the amount of stretch or compression you apply. If the applied force is not too large, the restoring force is proportional to the distance the mass is moved from its equilibrium position. If the force is too large, the spring will be permanently stretched and not return to its original length. In the discussion that follows, we assume that the stretch of the system is not too large. Many natural phenomena obey this condition, so little is lost by imposing this constraint.

Imagine pulling the mass down a short distance and releasing it as shown in Figure 15-2(a). Initially, a net upward force accelerates the mass upward. As the mass moves upward, the net force decreases in size (b), becoming zero when the mass reaches the equilibrium position (c). Because the mass has inertia, it overshoots the equilibrium position. The net force now acts downward (d) and slows the mass to zero speed (e). Then the mass gains speed in the downward direction (f). Again, the mass passes the equilibrium position (g). Now the net force is once again upward (h) and slows the mass until it reaches its lowest point (a). This sequence [Figure 15-2(a through a)] completes one **cycle.**

Actually, a cycle can begin at any position. It lasts until the mass returns to the original position *and* is moving in the same direction. For example, a cycle may begin when the mass passes through the equilibrium point on its way up (c) and end when it next passes through this point on the way up. Note that the cycle does not end when the mass passes through the equilibrium point on the way down (g). This motion is known as periodic motion, and the amount of time required for one cycle is known as the **period** T.

period is the time to complete one cycle ▶

If we ignore frictional effects, energy conservation (Chapter 7) tells us that the mass travels the same distance above and below the equilibrium position.