4 Isaac Newton and the Laws of Motion

KEY IDEA

Newton's laws of motion describe the behavior of objects on Earth and in space.

PHYSICS AROUND US . . . Getting Around

Travelling fast is so much a part of our modern society that we barely give it a thought. You board a train, sit back in a comfortable seat, and begin to read. You barely notice the feeling of being pushed back into your seat as the train accelerates and leaves the station.

An hour into your journey, you walk back to the snack bar for a doughnut and a cup of coffee. The train sways slightly as you return to your seat, but you're moving so steadily that you don't spill a drop, you make it back to your seat with no mishaps. You hardly notice the motion of the train again until you feel a slight forward pull as you slow down and stop at a station.

The high-speed bullet train above can reach a speed of 175 miles per hour in a straight line. However, the laws that govern its motion are the same no matter what speed it attains.

Every moment of our lives we are subjected to forces and motions. They're so much a part of our daily routine that we scarcely notice the deep and satisfying order that underlies all of these events—an order codified in Newton's laws of motion.

CLASSICAL MECHANICS

Kepler's laws of planetary motion and Galileo's work on falling bodies (see Chapter 3) each describe the motion of objects in a particular situation, but neither is a general description of motion. Kepler's laws, for example, don't tell you how to calculate the trajectory of a space probe. Similarly, Galileo's law of compound motion isn't much help if you want to know how quickly your car can accelerate from 0 to 60 miles per hour. To answer these sorts of questions, we need a theory that tells us how any object is affected by any force. Traditionally, the field of study that deals with these sorts of questions is known as *classical mechanics.*

Isaac Newton (1642–1727).

The man who took the scientific process from the work of Galileo and Kepler to a full-fledged science of mechanics was an Englishman named Isaac Newton (1642–1727). Arguably the greatest scientist who ever lived, Newton made significant contributions to many areas of science and mathematics (see Physics in the Making). However, his most important contributions for our present discussion came in two closely related areas. First, he developed a science of mechanics based on what we now call **Newton's laws of motion.** These three simple laws describe how any object in the universe behaves when acted on by any force. Second, he described the effects of one of the fundamental forces that govern the universe—the force of gravity. Using Newton's discoveries, subsequent generations of scientists were able to develop a comprehensive view of motion in the universe. That sweeping view incorporated everything—from the flow of blood in an artery to the rotation of a distant galaxy—into a single coherent framework. Because of Newton's role in these developments, the area of physics you are about to study is often referred to as *Newtonian mechanics* and the philosophical ideas that grew from it as the *Newtonian worldview.*

Three basic laws form the centerpiece of Newton's description of motion. They sound simple and obvious, although they are actually quite subtle and profound. These three statements represent the results of centuries of experiment and observation, but as stated by Newton, they had an extraordinary effect on the development of science.

Physics in the Making

Newton's Miraculous Year

Sixteen-sixty-five was not a good year for Cambridge University. Bubonic plague (the Black Death) was making one of its periodic appearances in England, and people fleeing the cities were spreading the disease everywhere. In some towns the situation got so bad that convicts who had been sentenced to be hanged were given the chance to escape their fate by burning the bodies of plague victims. Each morning they wheeled their carts through the streets, calling, "Bring out your dead," and then took the bodies outside the city for cremation.

In situations like these, even university administrations take action. They closed Cambridge University, sending the students back to their homes until the plague abated. For most students and teachers it was probably just a vacation, but for one young man named Isaac Newton the break provided a chance to think on his own, without the distractions of the university. By the time the university opened again 18 months later he had developed (1) a new branch of mathematics known as calculus, (2) the basis for the modern theory of color, (3) the statements of the laws of motion, (4) the law of universal gravitation (which, as we'll see, connected the sciences of physics and astronomy), and, in his spare time, polished off a few mathematical problems that had eluded solution up to that time. In his words, "In those days I was in the prime of my age for invention, and minded Mathematics and Philosophy more than at any time since."

Newton's work formed the basis for most of the scientific and technological discoveries that led to the Industrial Revolution. Even today his ideas are still essential for our basic understanding of science. Little wonder that historians refer to 1665 as Newton's "annus mirabilis," or miraculous year.

THE FIRST LAW

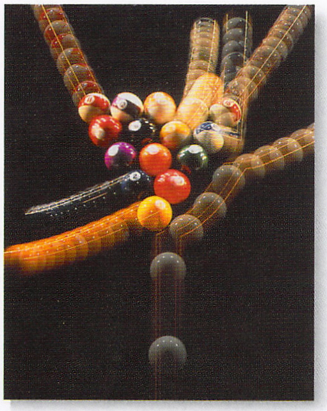
Newton's first law of motion links the key concepts of motion and force.

A moving object will continue moving in a straight line at a constant speed, and a stationary object will remain at rest, unless acted on by an unbalanced force.

Baseball hit for a home run.

Read Newton's first law again, and think about what it means. An object that is moving will continue to move, and an object that is just sitting on a table will continue to sit on the table, *unless* you exert a force on it. It seems self-evident to us that if you leave something alone, it won't change its state of motion. A bowling ball keeps rolling down the lane until it hits the pins. Your car won't change direction unless you turn the steering wheel. A skater glides across the ice until she does something to change direction.

However, virtually all scientists from the ancient Greeks to Copernicus would have argued that Newton's first law of motion is wrong. They were not able to take the step that Galileo and Newton took by separating out the effects of friction on an object's motion. These scientists believed that since the circle is the most perfect geometrical shape, heavenly bodies move in circles unless something interferes. This is why, in their theories, the heavenly spheres kept turning forever.



Pool balls are an example of how uniform motion can suddenly change because of a force.

Newton, basing his arguments on observations and the work of his predecessors, especially Galileo, turned this notion around. A moving object left to itself travels in a straight line. If you want to get it to move in a circle, you have to apply a force. You know this is true from your own experience. If you swing something around your head, such as a ball tied to a string, it moves in a circle only so long as you hold on to it. Let go, and off it flies in a straight line.

Newton's first law tells us that when we see a change in an object's motion, then something must have acted to produce that change. As we saw in Chapter 3, *acceleration* is defined as any change in speed, any change in direction, or any combination of the two.

The first law states that any acceleration is a consequence of the action of a force. In this way, the first law of motion establishes the intimate connection between an acceleration and a force. Indeed, this law defines **force** as a phenomenon that can produce a change in an object's state of motion. This definition provides a simple way of recognizing forces in nature. In fact, we'll use the first law of motion extensively in this book to tell us how to recognize when a force, particularly a new kind of force, is acting.

Inertia

We sometimes give the tendency of an object to remain in uniform motion—to resist changes in its state of motion—the special name **inertia.** In fact, Newton's first law of motion is sometimes called the law of inertia. Inertia is why your body presses back into your seat when your car accelerates forward, and why your body pushes forward against your seat belt when you hit the brakes.

Inertia is another one of the many terms in physics that's also often used in everyday speech. You might speak of the inertia in a company or government organization when you want to get across the idea that it is resistant to change. The physics definition is that inertia resists changes in motion.

Develop Your Intuition: Inertia

Have you ever been in a restaurant and had difficulty getting the ketchup out of a glass bottle? How could inertia help you get it out?

If you're like most people, you held the bottle upside down and shook it vigorously. When the ketchup came out with a plop, you were seeing inertia in operation—a successful application of Newton's first law of motion. Here's how it works.

When you held the bottle upside down and started moving it down, you gave everything in your hand—the bottle and its contents—downward velocity imparted by the force of your hand. When you suddenly stopped the motion of your hand, you caused a change in the state of motion of the bottle. The ketchup, however, is not slowed down by your hand, but only by the friction between itself and the walls of the bottle. Consequently, it obeys Newton's first law of motion and keeps moving in a straight line.

"Plop!"

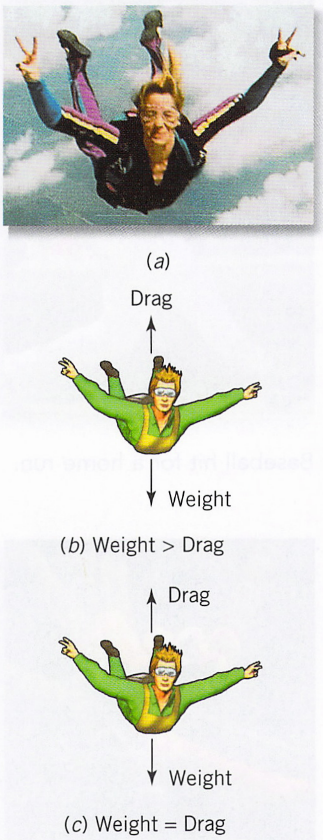


FIGURE 4-1. (*a*) A skydiver at terminal velocity falls with a constant speed. (*b*) Weight is greater than drag. Velocity is increasing, and there is acceleration downward. (*c*) Weight equals drag. Velocity is constant, and acceleration equals zero.

Balanced and Unbalanced Forces

One important aspect of the first law lies in the innocuous word "unbalanced." This word has to do with what happens when more than one force acts on an object. The unbalanced force on an object is often referred to as the *net force* acting on it. In the more complicated situations in which two or more forces act in different directions, the net force is sometimes called the *resultant force.*

To illustrate what we mean, imagine a skydiver jumping out of an airplane (see Figure 4-1*a*). We know that gravity acts on the skydiver, pulling her downward. But we also know that as she starts to fall she must push the air aside, and this push results in another force acting on her—a force engineers call *drag,* or *air resistance.* This force is directed upward (i.e., in the opposite direction to gravity) and it increases as she falls faster and faster. So as the skydiver falls, we can distinguish two distinct situations.

Unbalanced Force At the beginning of her fall, the skydiver is moving slowly, so the drag force is small (Figure 4-1*b*). Consequently, the downward force of gravity is much larger than the drag force. We define the *unbalanced force* on the skydiver as the difference between the downward and upward forces. At the start of the fall, then, this force is directed downward. This net force—the sum of all the forces acting on an object—is referred to as the *unbalanced force* in the first law of motion. According to this law, the skydiver should accelerate as she starts to fall—something we know to be true from everyday experience. She continues to accelerate as long as there is an unbalanced force acting.

Balanced Forces As the falling skydiver speeds up, the drag force grows. Eventually, the upward drag force equals the downward force of gravity (Figure 4-1*c*). At this point, the net force (gravity minus drag) is zero. There is no unbalanced force on the skydiver. According to the first law of motion, the balanced pair of forces means that the skydiver's acceleration goes to zero. Whatever velocity she had at the point where the net force went to zero is the velocity she has from that point on. This final speed is called the *terminal velocity.* For a skydiver falling toward the Earth the terminal velocity is typically about 100 miles per hour. Of course, once the parachute opens, the drag is greatly increased and the skydiver's velocity drops to just a few miles per hour.

Why doesn't a falling object stop moving when the net force goes to zero? According to the first law of motion, *any* change of motion requires the action of an unbalanced force. Stopping a falling object in midair requires that the object be accelerated (remember that a deceleration is just a negative acceleration). The object can't slow down unless some unbalanced force is acting on it, and since the net force on the object is zero there can be no change in its state of motion. Consequently, it just keeps moving along at the same speed. It keeps falling at the terminal velocity.

Another common example of opposing forces is connected to the phenomenon of friction. If you try to slide a heavy desk along a floor, you know that once you get the desk moving, you have to keep exerting a force to keep it moving. Stop pushing and the desk decelerates and stops. A desk moving across the floor at constant speed is not accelerating. (Remember that in order to accelerate, an object's velocity has to change.) This means that the net force acting on it must be zero. Since you are pushing and exerting a force (to the right, for example), there must be another force acting to the left. This is the force of friction, and it is generated whenever two surfaces slide past each other.

If you could see the contact between the bottom of the desk and the floor, you would see that both surfaces consist of microscopic peaks and valleys. When you move one surface across the other, the bonds that hold atoms and molecules together are constantly being broken and re-formed. You have to overcome these forces when you're pushing the desk.

Develop Your Intuition: Force Exerted by a Chair

Use Newton's first law of motion to describe what happens when you (1) sit in a chair that holds you up, and (2) sit in a chair that collapses under you.

In the first case, you don't accelerate; so, according to Newton's first law, the net force acting on you must be zero. Two forces act on you: the Earth exerts a downward force on you (your weight) and the chair exerts an upward force on you. Since the net force equals zero, these two forces must be equal in magnitude. The chair is strong enough to exert a force that exactly balances the force of gravity (Figure 4-2).

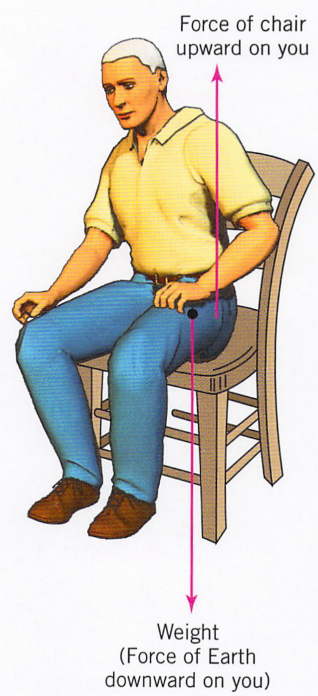


FIGURE 4-2. Vector diagram of a person sitting in a chair and the forces acting on him.

If, however, the chair is old and rickety, it might not be able to exert that much force. In this case, the net force is not zero and gravity will win. You will accelerate downward until you encounter an object (the floor, for example) capable of exerting an upward force equal to that exerted by gravity. Have you ever sat down in a chair that broke?

THE SECOND LAW

Newton's first law of motion tells you when a force is acting; the second law of motion tells you what the force does when it acts. The precise statement of the second law is:

When a net force acts on an object, the object accelerates in the same direction as that force. The acceleration is directly proportional to the net force and inversely proportional to the mass of the object.

The **mass** of an object is simply the amount of matter contained in that object.

Newton's second law conforms to our everyday experience that it's easier to propel a bicycle than a car, easier to lift a child than an adult, and easier to deflect a ballerina than a defensive tackle. The second law of motion can be described as an equation.

1. In words:

The bigger the force, the greater the acceleration; the larger the mass, the smaller the acceleration.

2. In an equation with words:

Force = Mass (in kilograms) × Acceleration (in meters per second²)

3. In an equation with symbols:

$$F = m \times a$$

This equation, well known to generations of physics students, tells us that if we know the forces acting on a system of known mass, we can predict its future motion. Newton's second law supports our intuition that an object's acceleration is a balance between two factors. On the one hand, a net force causes an acceleration; therefore, the greater the net force, the greater the acceleration. The harder

A small force can cause a change in motion of a large object.

you throw a ball, the farther it goes; the harder you pedal a bike, the faster it goes. According to the second law of motion, the acceleration of an object is directly proportional to the net force applied.

On the other hand, the greater the object's mass—the more stuff you have to accelerate—the less effect a given force is going to have. A given force accelerates a golf ball more than a bowling ball, for example, and it takes twice as much force to start two chairs moving along the floor as it does to start one moving. In this way, Newton's second law of motion defines the balance between force and mass in producing an acceleration. Recasting the equation, we can see that acceleration is inversely proportional to mass:

$$\text{Acceleration} = \frac{\text{Force}}{\text{Mass}}$$

The Unit of Force

In the English system, force is measured in the familiar unit of the pound. In SI, the unit of force is called the **newton** (abbreviated N). Think about the second law's definition of force as mass times acceleration. A *newton* is defined as the force that accelerates a 1-kilogram mass at the rate of 1 meter per second per second.

$$1 \text{ N} = 1 \text{ kg-m/s}^2$$

For comparison, a 1-pound force is equal to about 4.45 N. See Looking at Force on page 86 for other examples of forces.

LOOKING DEEPER

When Forces Don't Act in the Same Direction

When more than one force acts on an object, but the forces don't act in the same direction, the recipe for finding the net force and resultant motion is a little more complicated. Any force can be represented as a vector—that is, as an arrow in which the direction of the arrow represents the direction of the force and the length of the arrow represents the strength, or magnitude, of the force. In Chapter 2 we learned how to add vectors that do not act in the same direction. When two forces act together, the resultant force is just the sum of the two vectors placed head to tail. In Figure 4-3 we show an example of such a situation. The two forces, shown as vectors *A* and *B*, act on a single object. On the right, we show the triangle whose sides are the vectors *A* and *B*, placed head to tail. The resultant force is shown as vector *C*, the third side of the triangle. This force has a magnitude equal to the length of *C* and points in the direction of *C*, as shown.

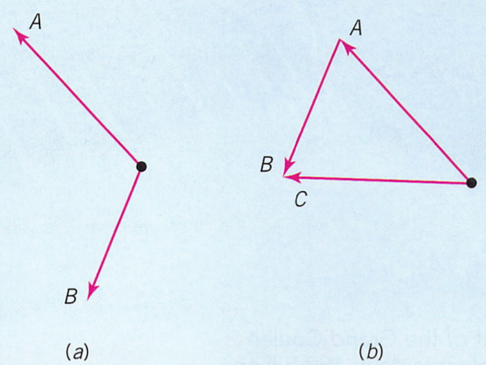


FIGURE 4-3. Vector addition of forces. (*a*) Forces *A* and *B* act on an object. (*b*) When vectors *A* and *B* are placed head to tail, the third side of the triangle is their sum, vector *C*.

If more than two forces are acting, you can find the resultant force for all of them by finding the resultant force for two, then finding the resultant force of that force with a third, then combining *that* resultant force with a fourth, and so on. Remember, no matter how many forces act, the object can accelerate in only one direction and the net effect must be the same as a single force.

Looking at Force

An apple weighs about 1 newton, or a quarter of a pound, roughly the same as a good-sized hamburger. That's a lot more than the force of attraction in the bonds of molecular DNA, about 10^{-7} N—although each molecule of DNA has about 100,000 such bonds. When it comes to large forces, consider the structures built to support roads, fly through the air, or control the flow of rivers. These are truly forces to reckon with.

10^{-7} N

DNA bonds, 10^{-7} newton (0.25×10^{-7} pound)

10^{0} N

Weight of an apple: 1 newton (0.25 pound)

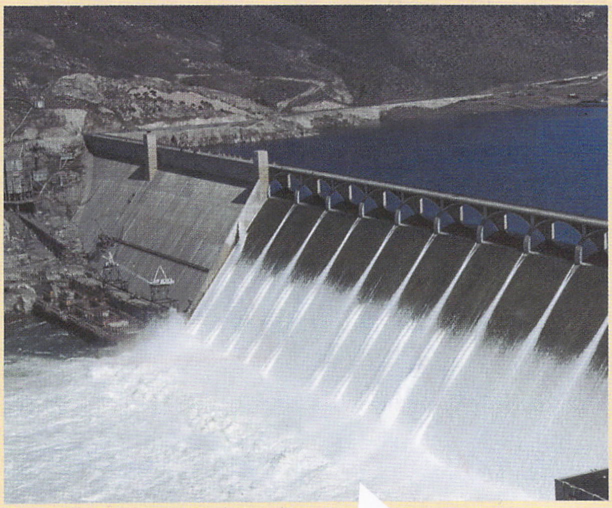
10^{6} N

Thrust of an airliner: 1 million newtons (250,000 pounds)

10^{9} N

Tension in the cables of the Verrazano Narrows Bridge: 1.1 billion newtons (250 million pounds)

10^{11} N



Weight of the Grand Coulee hydroelectric dam: 190 billion newtons (43 billion pounds)

THE THIRD LAW

Newton's third law of motion tells us that whenever a force is applied to an object, that object simultaneously exerts an equal and opposite force on whatever is applying the initial force.

For every action (force) there is an equal and opposite reaction (force).

For example, when you push on a wall it pushes back on you; you can feel the force on the palm of your hand. In fact, the force the wall exerts on you is equal in magnitude, but opposite in direction, to the force you exert on it. And the harder you push on the wall, the harder it pushes on you.

FIGURE 4-4. A pianist presses down on the piano keys to make the notes sound; the keys press back up on the pianist's fingers.

The third law of motion is perhaps the least intuitive of Newton's three laws. We tend to think of our world in terms of causes and effects, in which big or fast objects exert forces on smaller, slower ones. A pianist pushes down on the piano key to produce a note. A basketball player pushes down on the ball to bounce it. A meteorite streaks down from space and smashes into the surface of the Earth. What the third law tells us is that there is another way to look at each of these situations. The pianist does, indeed, exert a force on the key, but at the same time the key exerts an equal and opposite force on the pianist, bringing the motion of the finger to a stop (Figure 4-4). As the basketball player exerts a force on the ball, the ball exerts an equal and opposite force on his hand. (Figure 4-5). And even as the meteorite smashes into the solid Earth, the Earth exerts an equal and opposite force on the meteorite. The third law tells us that every time one object exerts a force on another object, the second object exerts an equal and opposite force on the first. Forces always come in pairs.

One important point about Newton's third law—a point that often causes a great deal of confusion—is that while it's true that forces always come in action–reaction pairs, *the two forces in this pair act on different objects.* The force exerted by the pianist's finger pushes on the key, but the force exerted by the key pushes on the pianist's finger. When you push on the wall, the force you exert acts on the wall. The force could, in principle, accelerate the wall (if you were pushing over a loose pile of bricks, for example). However, the force you exert on the wall cannot accelerate you because it does not act on you. The force exerted by the wall does act on you, and could cause you to accelerate. For example, if you bumped into the wall while running, you might bounce backward. Ouch!

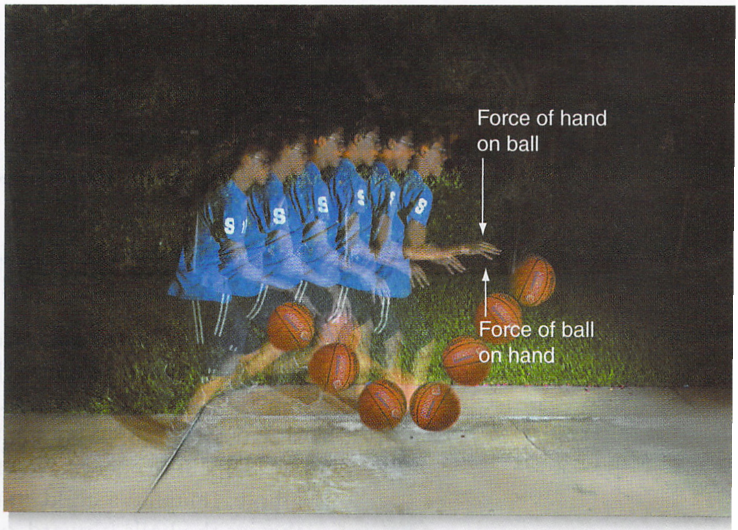


FIGURE 4-5. This strobe photo of a ball being dribbled shows that when you push on the ball, the ball exerts a force back on you.

Develop Your Intuition: A Horse and Cart

Here's a conundrum often used to bedevil beginning physics students: think about a horse and a cart. The horse exerts a forward force on the cart, but the cart exerts an equal and opposite backward force on the horse. How can the horse and cart possibly move forward?

The key to resolving this dilemma is to remember that Newton's second law of motion says that acceleration of an object results from the action of a net force *on that same object.* Take the horse, for example. It pulls on the cart, and therefore there is a backward force exerted on it by the cart. However, the horse also pushes backward against the Earth so there is a reaction force exerted on the horse by the Earth, and this force acts in the forward direction. If the horse pushes hard enough, the forward reaction force exerted on it by the Earth will be larger than the backward force of the cart, and the horse will move forward (Figure 4-6). The cart exerts a force on the horse and the horse exerts a force on the cart, but these two forces are not acting on the same object and so cannot be counted as part of the same net force causing an acceleration.

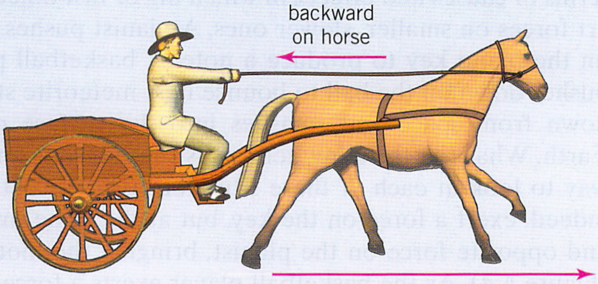


FIGURE 4-6. The horse pulls forward on the cart and the cart pulls backward on the horse. How can they move? Vector diagram of the horse shows only those forces acting on a single object.

If the surface is slippery (ice, for example), it's harder for the horse to push backward, so that the reaction force of the Earth is less, and the horse may not be able to move the cart. Have you ever tried to move a heavy object (a sled loaded with firewood, for example) on an icy surface and had your feet slip out from under you?

NEWTON'S LAWS TAKEN TOGETHER

Isaac Newton's three laws of motion form a comprehensive description of all possible motions. Taken together, they give us a way of analyzing everything in the universe, from billiard balls rolling on a table to the track of a space probe. In many situations, all three laws have to be used together to analyze a particular situation.

This interplay of Newton's three laws of motion can be seen in a simple example. Imagine a child standing on roller skates holding a stack of baseballs. He throws the balls forward, one by one. Each time he throws a baseball, the first law tells us that he has to exert a force so that the ball accelerates. The third law then tells us that the baseball exerts an equal and opposite force on him. This force acting on the child, according to the second law, causes him to recoil backward.

While the example of the child and the baseballs may seem a bit contrived, it illustrates the exact principle by which rockets work. In a rocket engine, forces are exerted on hot gases, accelerating them out the tail end of the rocket. As with the child on skates, the first law tells us that the rocket exerts a force on the gas, the third law reveals that the gases exert an equal and opposite force on the rocket, and the second law quantifies the amount that this reaction force causes the rocket to accelerate. Every rocket, from Fourth-of-July fireworks to the space shuttle, works this way.

Develop Your Intuition: Rockets in Space

In the early days of rocketry, prestigious publications such as the *New York Times* argued that rockets could never work in space because there was no air for them to push against. If the exiting gases didn't push against any air, there would be no reaction push by the air against the rocket. How would you answer this argument using Newton's laws?

The fact is that a rocket works because of the reaction force exerted by exhaust gases against the rocket itself, not by the force the gases exert on the air (Figure 4-7). Thus, the rocket works whether there is air around it or not. The Apollo landings on and takeoffs from the Moon demonstrated convincingly that a rocket could indeed work in the absence of air.

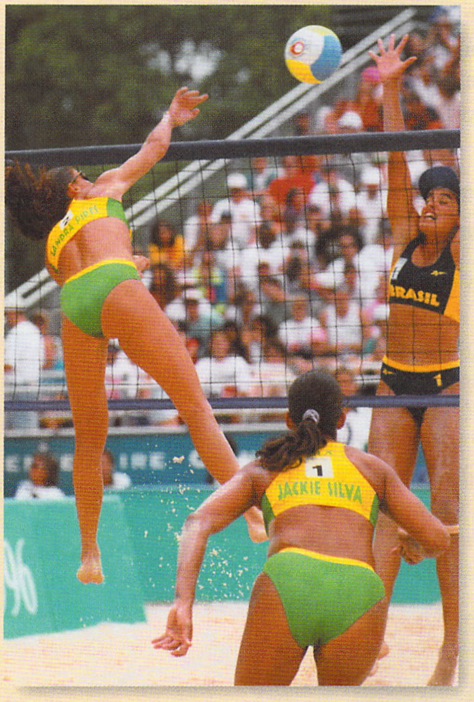
FIGURE 4-7. The space shuttle *Discovery* rises from its launch pad at Cape Canaveral, Florida. As hot gases accelerate violently out the rocket's engine, the shuttle experiences an equal and opposite acceleration that lifts it into orbit.

THINKING MORE ABOUT

Newton's Laws of Motion: Isaac Newton Plays Volleyball

Newton's three laws of motion apply to every action of our lives. Think about a game of doubles volleyball at the beach. It's a beautiful sunny day with a light breeze off the ocean. The opposing team serves the ball low and hard, but your partner gives you a perfect pass. You set the ball high and outside, a foot off the net. She makes her approach, leaps high, and hits down the line for a side out.

During this one brief play, dozens of forces and motions took place. The ball changed direction and speed, players ran and jumped, sand



Newton's laws of motion apply everywhere, including the volleyball court.

grains shifted, and the wind blew while waves crashed in the background. Think about how Newton's laws of motion apply to these events.

The first law says that nothing happens without an unbalanced force. When a ball flies through the air or a person jumps high off the ground, a force must be involved. One everyday force is gravity, which causes the ball (and the players) to fall back to Earth. Contact forces, such as occur when the player's hand strikes the ball or when she leaps into the air by pushing against the sand, are also all around us. The origin of other forces, such as those that cause the wind to blow or waves to crash onto the shore, are less obvious. But whatever the event, Newton's first law of motion tells us that a force must exist.

Newton's second law of motion allows us to calculate exactly how much force must be applied to achieve a given result (force equals mass times acceleration). A hard serve requires more force than a dink serve, just as a 36-inch vertical jump demands more force than a 12-inch jump. Volleyball players can't stop to perform complex mathematical calculations in the middle of their game. Nevertheless, our cumulative experience, living in a world of forces and motions, gives us a pretty good idea about how much force to use in a given situation. And the more you practice a sport, the better your intuition becomes about forces, motions, and Newton's second law.

Newton's subtle third law of motion comes into play throughout the volleyball game: all forces occur in pairs. As the player hits the ball, applying a force to propel it forward, the player's hand feels the force of the ball pushing back. (If you've ever received a painfully hard spike, you'll know about forces acting in pairs.) When you push down to jump high off the sand, the sand pushes with an equal and opposite force against you. As the wind blows against your hair, your hair simultaneously changes the path of the wind.

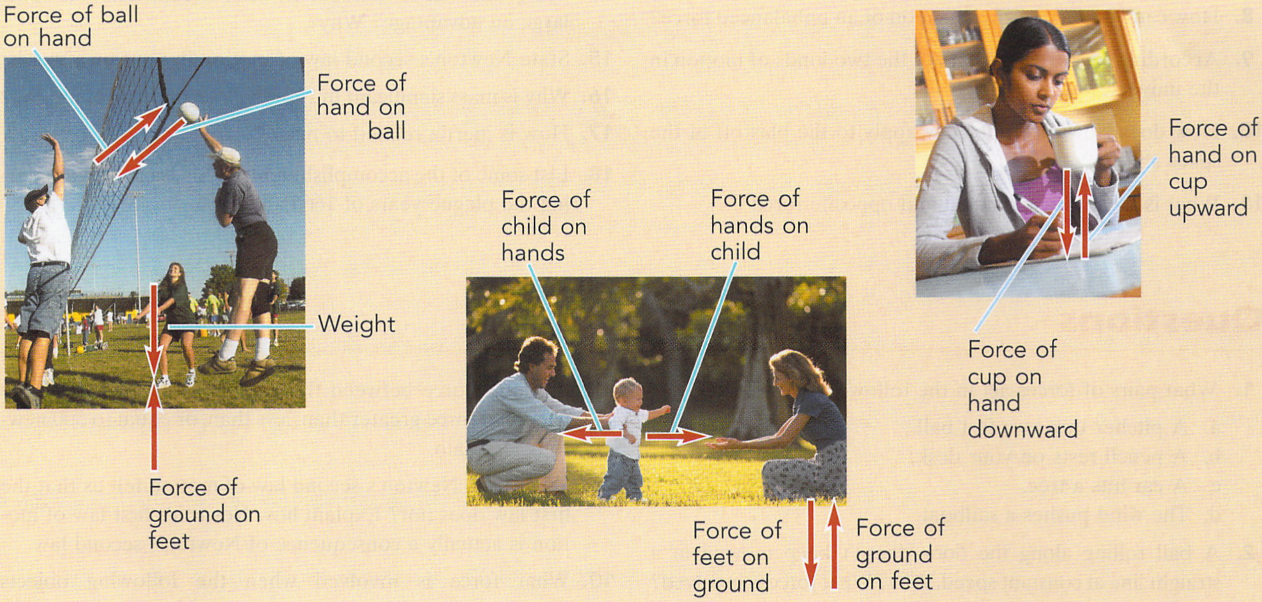
Some time when you're taking a walk, look at what goes on around you and think about how Newton's three laws of motion relate to what you see. What forces are involved when a car slows down, a leaf falls, or a squirrel runs up a tree? What is the unceasing interplay of forces and motions at work when you ride a bike, read a book, use a computer, or attend a concert? (For some other examples, look at Physics and Daily Life on p. 91. Can you identify the forces acting and the objects each force acts on? Can you identify the action–reaction pairs of Newton's third law?)

Summary

Isaac Newton combined the work of Kepler, Galileo, and others in his three **laws of motion.** The first law of motion states that nothing accelerates without an unbalanced **force** acting. Without an unbalanced force, objects remain at rest or in constant motion. **Inertia** is the tendency of an object to remain in uniform motion—to resist changes in its state of motion. The second law of motion quantifies net force (measured in **newtons**) in terms of the **mass** and acceleration of an object. The amount of acceleration is proportional to the force applied and inversely proportional to the mass. The third law of motion states that forces always act in equal and opposite pairs. Taken together, these three laws describe motions on Earth and in space.

Physics and Daily Life–Forces

Forces appear all around us all the time, although we may not be aware of them. Weight is a force and holding an object in the air also requires a force. And any time you change an object's motion—hit a volleyball, walk across the grass, raise your glass in a toast—you exert forces, while forces are exerted on you.



Key Terms

force (measured in newtons) A phenomenon that can produce a change in an object's state of motion. (p. 81)

inertia The tendency of an object to remain in uniform motion—to resist changes in its state of motion. (p. 82)

mass The amount of matter contained in an object, independent of where that object is found. (p. 84)

newton (N) The SI unit of force that accelerates a 1-kilogram mass at the rate of 1 meter per second per second. (p. 85)

Newton's laws of motion Three laws that describe how any object in the universe behaves when acted on by any force; the *first law* states that a moving object will continue moving in a straight line at a constant speed, and a stationary object will remain at rest, unless acted on by an unbalanced force; the *second law* states that the acceleration produced on a body by a force is proportional to the magnitude of the force and inversely proportional to the mass of the object; the *third law* states that for every action (force) there is an equal and opposite reaction (force). (p. 80)

Key Equation

Force = Mass × Acceleration

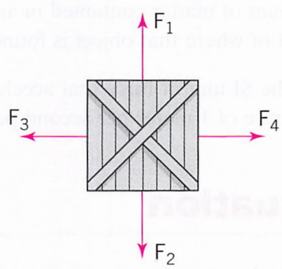
Review

1. What is Isaac Newton's first law of motion? Give an everyday example of this law in action.
2. What is inertia? Give an everyday example of this phenomenon.
3. What is the force that causes a ball rolling on the floor to slow down and stop?
4. What is Isaac Newton's second law of motion? Give an everyday example of this law in action.

5. What is Isaac Newton's third law of motion? Give an everyday example of this law in action.
6. What is a force? What is the unit of force?
7. What is an unbalanced force? How does it relate to the net force?
8. How can you recognize the action of an unbalanced force?
9. According to Newton, what are the two kinds of motion in the universe?
10. How does Newton's third law apply to the blastoff of the space shuttle?
11. What is meant by an "equal and opposite force"?
12. Review how Newton's laws of motion come into play during a volleyball game.
13. Pick an everyday activity and discuss how Newton's three laws of motion come into play.
14. Think about your favorite sport. In what circumstances is being small an advantage? In what circumstances is being large an advantage? Why?
15. State Newton's second law of motion in your own words.
16. Why is mass significant in Newton's second law of motion?
17. How is inertia related to mass?
18. List some of the accomplishments of Sir Isaac Newton during the plague years of 1665 and 1666.

Questions

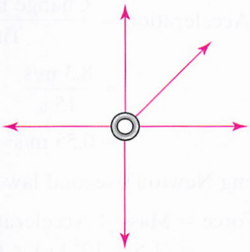
1. What pairs of forces act in the following situations?
   a. A pitcher throws a fast ball.
   b. A pencil rests on your desk.
   c. A car hits a tree.
   d. The wind pushes a sailboat.
2. A ball rolling along the floor doesn't keep moving in a straight line at constant speed. Why? What force is involved?
3. When you are moving up at constant speed in an elevator, there are two forces acting on you: the floor pushing up on you and gravity pulling down. Compare the strengths of these two forces. Explain your answer in terms of Newton's first law of motion.
4. You step into an elevator at the 10th floor and press the 2nd-floor button. The elevator accelerates downward briefly as it picks up speed. There are two forces acting on you: the floor pushing up on you and gravity pulling down. Compare these two forces while the elevator is accelerating downward. Explain your answer in terms of Newton's second law of motion.
5. A passenger on a Ferris wheel moves in a vertical circle at constant speed. Is she accelerating? Are the forces on her balanced? Explain.
6. A 28,000-pound jet airliner cruises at 500 miles per hour and an altitude of 35,000 feet. The forward thrust of the engines is 10,000 pounds. Assuming the plane maintains altitude and speed, what is the total air drag force pushing back on the plane? What is the total lift force pushing up on the plane? Explain.
7. A rocket blasting into space provides an example of Newton's third law of motion. Outline the forces acting on the rocket as well as on the propellants.
8. In order to slide a heavy desk across the floor at constant speed, you have to exert a horizontal force of 500 newtons. Compare the 500-newton horizontal pushing force to the frictional force between the desk and the ground. Is the frictional force greater than, less than, or equal to 500 newtons? Explain.
9. What does Newton's second law of motion tell us that the first law does not? Explain how Newton's first law of motion is actually a consequence of Newton's second law.
10. What force is involved when the following objects accelerate:
    a. A sailboat changes direction.
    b. A car turns a corner.
    c. A leaf falls from a tree.
    d. You turn a page of this book.
11. A race car drives along a straight track at constant speed. Are the forces acting on the driver balanced? Explain.
12. A heavily loaded freight train moves with constant velocity. Compare the net force on the first car to the net force on the last car. Explain.



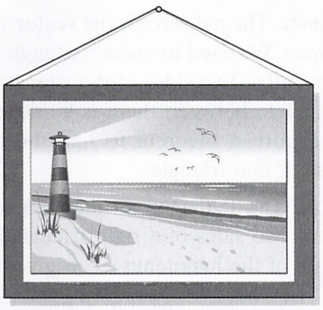
Questions 13, 14

13. In the figure, if the box is accelerating to the right, compare F_1 to F_2 and F_3 to F_4.
14. In the figure, if the box is accelerating upward and to the right, compare F_1 to F_2 and F_3 to F_4.
15. Five 10-N forces (represented by arrows in the figure) act on ropes connected to an iron ring in the directions shown.

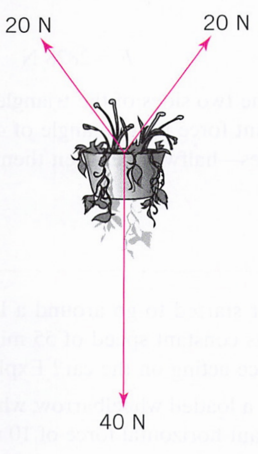
Will the ring experience acceleration? If so, in what direction will it accelerate? Explain.



16. A picture hangs on the wall, supported by a wire connected to two corners of the picture frame, as shown. Draw two arrows that represent the two forces that the wires exert on the picture frame. Draw another arrow that represents the addition of those two forces.



17. Two 20-N forces and a 40-N force act on a hanging plant as shown. Will the plant experience acceleration? If so, in what direction will it accelerate? Explain.



18. When a rocket is launched, it carries a heavy load of fuel, which is burned during the ascent. How does the mass of the rocket change as it climbs up on its trajectory? Is the force needed to produce a given acceleration a few minutes after launch larger or smaller than the force needed to produce the same acceleration just off the launching pad?

19. In modern physics, we often talk about forces in terms of an exchange of particles between objects. To see how this might work, imagine the following situation. Two students are running side-by-side in a straight line to catch a train. One is carrying a heavy suitcase and halfway to the train he throws it over to his friend.

a. What forces are created as a result of the throwing of the suitcase?

b. What forces are created as a result of the friend catching the suitcase?

c. As a result of the change, are the students forced to deviate from straight line motion? Explain.

20. A bicycle rider accelerates from rest up to full speed on a flat, straight road. Compare the frictional force between the road and the tires pushing her forward to the air drag (and other frictional forces) pushing back: a. in the first few seconds of the ride, and b. after she has reached full speed.

21. When an object is moving in air, the air drag force is in the opposite direction to the velocity. A light foam ball is thrown up into the air. When is the net force on the ball the greatest: When it is moving up, when it is at the top of its trajectory, or when it is moving down? Explain.

22. A car is driving up a straight hill at a constant speed of 50 kilometers per hour. Is the net force on the car zero? A second car is driving over the crest of the hill at a constant speed of 50 miles per hour. Is the net force on the car zero?

23. When you kick a soccer ball, thus applying a force to the ball, what is the equal and opposite force? Which force is greater?

24. A female gymnast weighs 400 N. If she is hanging stationary from a high bar, what are the two forces acting on her? Compare the strength of those forces.

25. What is wrong with this statement: In a tug-of-war contest between two people, the person who pulls harder usually wins. (Assume the rope is light and it does not slip in either person's hands.)

Problem-Solving Examples

EXAMPLE 4-1 The Blue Whale

An adult blue whale, the largest animal on Earth, can have a mass as high as 150,000 kilograms (330,000 pounds). How much force must such a whale generate with its massive tail to achieve its swimming velocity of 30 kilometers per hour in 15 seconds?

REASONING: Newton's second law of motion says that force equals mass (in kilograms) times acceleration (in meters per second per second), so we need to know both the mass and the acceleration to calculate force. The mass is given as 1.5×10^5 kg. The acceleration is 30 kilometers per hour in 15 seconds, which must be converted to standard units of meters per second per second. To do this, first recognize that 30 kilometers equals 3×10^4 meters and 1 hour equals 3600 seconds.

$$30 \text{ kilometers/hour} = \frac{3 \times 10^4 \text{ meters}}{3600 \text{ seconds}}$$

$$= 8.3 \text{ m/s}$$

The change in velocity is thus 8.3 meters per second in 15 seconds.

$$\text{Acceleration} = \frac{\text{Change in velocity}}{\text{Time}}$$

$$= \frac{8.3 \text{ m/s}}{15 \text{ s}}$$

$$= 0.55 \text{ m/s}^2$$

Now, applying Newton's second law

$$\text{Force} = \text{Mass} \times \text{Acceleration}$$

$$= (1.5 \times 10^5 \text{ kg}) \times (0.55 \text{ m/s}^2)$$

$$= 82{,}500 \text{ newtons}$$

That's equivalent to almost 10 tons of force! ●

EXAMPLE 4-2 The Sum of Forces in Two Directions

A tree-removal team wants to direct the fall of a tree away from a house and power lines. To do this, they attach two ropes to the tree, as shown in Figure 4-8. The angle between the ropes is 90 degrees and the pull on each rope is 2000 N. What are the direction and magnitude of the net force acting on the tree?

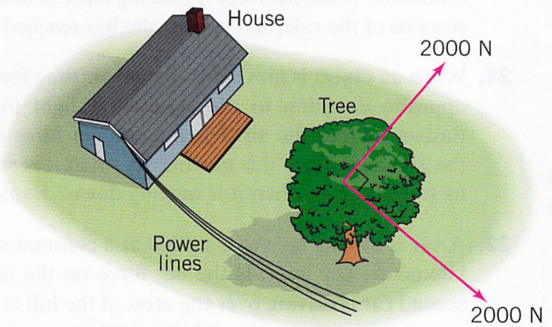


FIGURE 4-8. Pulling on ropes to deflect the fall of a tree. The net unbalanced force is the sum of the forces exerted on the ropes.

REASONING: The net force is the vector sum of the two applied forces. We need to make a triangle to determine this resultant force. Two sides of the triangle are 2000 N long and the angle between them is 90 degrees. We then use the Pythagorean theorem to find the length of the hypotenuse of that triangle.

SOLUTION: The Pythagorean theorem tells us that if the lengths of two sides of a right triangle are a and b, then the length of the hypotenuse, c, is given by the equation

$$c^2 = a^2 + b^2$$

In this case, if we call the length of the resultant force F, we have:

$$F^2 = (2000)^2 + (2000)^2 = 8{,}000{,}000 \text{ N}^2$$

so that:

$$F = 2828 \text{ N}$$

Because the two sides of the triangle are of equal length, the resultant force is at an angle of 45 degrees from each of the ropes—halfway between them, in fact. ●

Problems

1. How much force must be applied during liftoff to accelerate a 20-kg satellite just enough to counter the Earth's gravitational acceleration of 9.8 m/s^2?
2. Which of these objects has the greatest inertia: a mosquito, a VW bug, or an ocean liner? Justify your response by creating a mental experiment that uses Newton's second law, which can relate mass and inertia.
3. You are driving a car down a straight road at a constant 55 miles per hour.
   a. Are there any forces acting on the car? If so, list them.
   b. Is there a net force or unbalanced force acting on the car? Explain.
   c. If the car started to go around a long bend, still maintaining its constant speed of 55 miles per hour, is there a net force acting on the car? Explain.
4. John pushes a loaded wheelbarrow, which is initially at rest, with a constant horizontal force of 10 newtons. The mass of the wheelbarrow is 15 kg. Neglect friction forces.
   a. What is the constant acceleration of the wheelbarrow?
   b. If John pushes the wheelbarrow for 3 seconds, what distance does the wheelbarrow cover during this time?
   c. What is the speed of the wheelbarrow after 3 seconds?
5. Suzie (50 kg) is roller-blading down the sidewalk going 20 miles per hour. She notices a group of workers down the

walkway who have unexpectedly blocked her path, and she makes a quick stop in 0.5 seconds.

a. What is Suzie's average acceleration in meters per second^2?
b. What force in newtons was exerted to stop Suzie?
c. Where did this force come from?

6. Margie (45 kg) and Bill (65 kg), both with brand new roller blades, are at rest facing each other in the parking lot. They push off each other and move in opposite directions, Margie moving at a constant speed of 14 ft/s. At what speed is Bill moving? (*Hint:* Recall from Newton's third law that Margie and Bill experience equal and opposite forces.)

7. Tracy (50 kg) and Tom (75 kg) are standing at rest in the center of the roller rink, facing each other, free to move. Tracy pushes off Tom with her hands and remains in contact with Tom's hands, applying a constant force for 0.75 seconds. Tracy moves 0.5 meters during this time. When she stops pushing off Tom, she moves at a constant speed.

   a. What is Tracy's constant acceleration during her time of contact with Tom?
   b. What is Tracy's final speed after this contact?
   c. What force was applied to Tracy during this time? What is its origin?
   d. What happened to Tom? If Tom moved, describe his motion, force, acceleration, and Tom's final velocity.

8. A fast-moving VW Beetle moving at 60 mph hit a mosquito hovering at rest above the road.

   a. Which bug (insect or VW) experienced the largest force?
   b. Which bug (insect or VW) experienced the greatest acceleration?

Investigations

1. Read a biography of Isaac Newton. Were all of his ideas about the physical world correct? What were his views on religion and mysticism?

2. Design an apparatus that could be used to determine the mass of an object in the weightlessness of space. (*Hint:* Apply Newton's second law of motion.)

3. Investigate how a sailboat can tack into the wind. What forces are involved? Is it possible for a sailboat to sail directly into the wind? Why?

4. Investigate the forces involved in launching the space shuttle into orbit. In the first seconds after liftoff, how much of the total force of the rocket engines is used to lift the fuel (as opposed to the shuttle itself)?

5. Investigate NASA's *Messenger* space probe, which will be launched in 2004 to orbit the planet Mercury. This complex mission will require more than 99 kilograms of fuel and other hardware for every pound of payload. What are the objectives of the mission? Why is so much mass of fuel required?

6. Propose a series of simple experiments that you might devise to test each of Newton's three laws in the laboratory. What measurements would you make? What would be the principal sources of error in these measurements?

WWW Resources

See the *Physics Matters* home page at **www.wiley.com/college/trefil** for valuable web links.

1. **www.physics.uoguelph.ca/tutorials/fbd/FBD.htm** The Free Body Diagram tutorial at the Department of Physics, University of Guelph.
2. **www-groups.dcs.st-and.ac.uk/~history/Mathematicians/Newton.html** A biographic site for Sir Isaac Newton.
3. **www-istp.gsfc.nasa.gov/stargaze/Snewton.htm** A NASA website summarizing Newton's Laws.
4. **www.physicsclassroom.com/Class/newtlaws/newtltoc.html** An animated Newton's Law's tutorial from physicsclassroom.com.