4 Newton's Second Law of Motion

1 Efrain Lopez shows that when the forces on the blue block balance to zero, no acceleration occurs. 2 Wingsuit skydivers do what flying squirrels have always done, but faster. They jump from mountains or airplanes and after high terminal speeds use a parachute to safely land. 3 When Emily Abrams kicks the ball, it undergoes acceleration.

Galileo introduced the concept of acceleration, the rate at which velocity changes with time—$a = \Delta v/\Delta t$. But what produces acceleration? That question is answered in Newton's second law. It is *force.* (Newton himself dealt first with momentum and impulse, topics we address in Chapter 6, but nowadays we like to start with acceleration and force.) Newton's second law links these fundamental concepts of acceleration and force to one more profound concept, *mass,* as given by the famous equation, $a = F/m$. Interestingly, although Newton's insights of nature bloomed before he was 24 years of age, he was 42 when he included his three laws of motion in what is generally acknowledged as the greatest scientific book ever written, the *Principia Mathematica Philosophiae Naturalis.* He wrote the work in Latin and completed it in 18 months. It appeared in print in 1687, but it wasn't printed in English until 1729, two years after his death. When asked how he was able to make so many discoveries, Newton replied that he found his solutions to problems not by sudden insight but by continually thinking very long and hard about them until he worked them out. We've treated his first law in Chapter 2, defined acceleration in Chapter 3, and in this chapter we combine what we've learned—Newton's second law of motion.

Isaac Newton
(1642–1727)

Force Causes Acceleration

FIGURE 4.1
Kick the ball and it accelerates.

Consider a hockey puck at rest on ice. Apply a force, and it starts to move—it accelerates. When the hockey stick is no longer pushing it, the puck moves at constant velocity. Apply another force by striking the puck again, and again the motion changes. Applied force produces acceleration.

Most often, the applied force is not the only force acting on an object. Other forces may act as well. Recall, from Chapter 2, that the combination of forces acting on an object is the *net force*. Acceleration depends on the *net force*. To increase the acceleration of an object, you must increase the net force acting on it. If you double the net force on an object, its acceleration doubles; if you triple the net force, its acceleration triples; and so on. This makes good sense. We say an object's acceleration is directly proportional to the net force acting on it. We write

$$\text{Acceleration} \sim \text{net force}$$

The symbol $\sim$ stands for "is directly proportional to." That means, for instance, that if one doubles, the other also doubles.

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Force Causes Acceleration

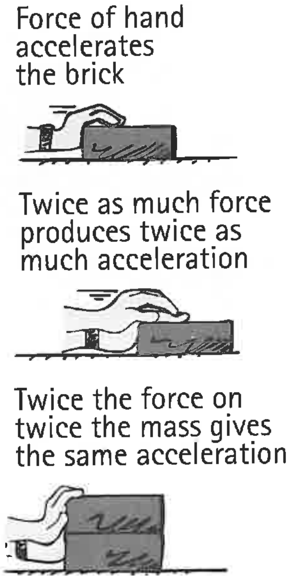

FIGURE 4.2
Acceleration is directly proportional to force.

CHECK POINT

1. You push on a crate that sits on a smooth floor, and it accelerates. If you apply four times the net force, how much greater will be the acceleration?
2. If you push with the same increased force on the same crate, but it slides on a very rough floor, how will the acceleration compare with pushing the crate on a smooth floor? *(Think before you read the answer below!)*

Check Your Answers

1. It will have four times as much acceleration.
2. It will have less acceleration because friction will reduce the net force.

Friction

When surfaces slide or tend to slide over one another, a force of friction acts. When you apply a force to an object, friction usually reduces the net force and the resulting acceleration. Friction is caused by the irregularities in the surfaces in mutual contact, and it depends on the kinds of material and how much they are pressed together. Even surfaces that appear to be very smooth have microscopic irregularities that obstruct motion. Atoms cling together at many points of contact. When one object slides against another, it must either rise over the irregular bumps or else scrape atoms off. Either way requires force.

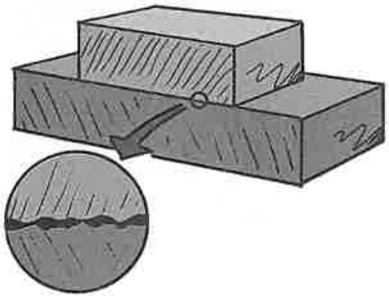

FIGURE 4.3
Friction results from the mutual contact of irregularities in the surfaces of sliding objects. Even surfaces that appear to be smooth have irregular surfaces when viewed at the microscopic level.

The direction of the friction force is always in a direction opposing motion. An object sliding *down* an incline experiences friction directed *up* the incline; an object that slides to the *right* experiences friction toward the *left*. Thus, if an object is to move at constant velocity, a force equal to the opposing force of friction must be applied so that the two forces exactly cancel each other. The zero net force then results in zero acceleration and constant velocity.

No friction exists on a crate that sits at rest on a level floor. But, if you push the crate horizontally, you'll disturb the contact surfaces and friction is produced. How much? If the crate is still at rest, then the friction that opposes motion is just enough to cancel your push. If you push horizontally with, say, 70 newtons, friction builds up to become 70 newtons. If you push harder—say, 100 newtons—and the crate is on the verge of sliding, the friction between the crate and floor opposes your push

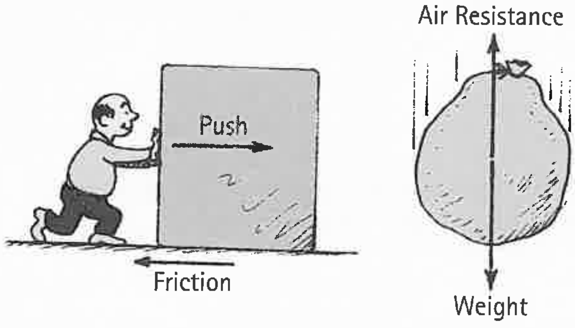

FIGURE 4.4

The direction of the force of friction always opposes the direction of motion. (Left) Push the crate to the right, and friction acts toward the left. (Right) The sack falls downward, and air friction (air resistance) acts upward. (What is the acceleration of the sack when air resistance equals the sack's weight?)

with 100 newtons. If 100 newtons is the most the surfaces can muster, then, when you push a bit harder, the clinging gives way and the crate slides.[1]

Interestingly, the friction of sliding is somewhat less than the friction that builds up before sliding takes place. Physicists and engineers distinguish between *static friction* and *sliding friction*. For given surfaces, static friction is somewhat greater than sliding friction. If you push on a crate, it takes more force to get it going than it takes to keep it sliding. Before the time of antilock brake systems, slamming on the brakes of a car was quite problematic. When tires lock, they slide, providing less friction than if they are made to roll to a stop. A rolling tire does not slide along the road surface, and friction is static friction, with more grab than sliding friction. But once the tires start to slide, the frictional force is reduced—not a good thing. An antilock brake system keeps the tires below the threshold of breaking loose into a slide.

It's also interesting that the force of friction does not depend on speed. A car skidding at low speed has approximately the same friction as the same car skidding at high speed. If the friction force of a crate that slides against a floor is 90 newtons at low speed, to a close approximation it is 90 newtons at a greater speed. It may be more when the crate is at rest and on the verge of sliding, but, once the crate is sliding, the friction force remains approximately the same.

More interesting still, friction does not depend on the area of contact. If you slide the crate on its smallest surface, all you do is concentrate the same weight on a smaller area with the result that the friction is the same. So those extra wide tires you see on some cars provide no more friction than narrower tires. The wider tire simply spreads the weight of the car over more surface area to reduce heating and wear. Similarly, the friction between a truck and the ground is the same whether the truck has four tires or eighteen! More tires spread the load over more ground area and reduce the pressure per tire. Interestingly, stopping distance when brakes are applied is not affected by the number of tires. But the wear that tires experience very much depends on the number of tires.

Friction is not restricted to solids sliding over one another. Friction occurs also in liquids and gases, both of which are called *fluids* (because they flow). Fluid friction occurs as an object pushes aside the fluid it is moving through. Have you ever attempted a 100-m dash through waist-deep water? The friction of fluids is appreciable, even at low speeds. So unlike the friction between solid surfaces, fluid friction depends on speed. A very common form of fluid friction for something moving through air is *air resistance,* also called *air drag*. You usually aren't aware of air resistance when walking or jogging, but you notice it at higher speeds when riding a bicycle or when skiing downhill. Air resistance increases with increasing speed.

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Friction

Tires have treads not to increase friction, but to displace and redirect water from between the road surface and the underside of the tire. Many racing cars use tires without treads because they race on dry days.

FIGURE 4.5

Friction between the tire and the ground is nearly the same whether the tire is wide or narrow. The purpose of the greater contact area is to reduce heating and wear.

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[1] Even though it may not seem so yet, most of the concepts in physics are not really complicated. But friction is different. Unlike most concepts in physics, it is a very complicated phenomenon. The findings are empirical (gained from a wide range of experiments) and the predictions approximate (also based on experiment).

The falling sack shown in Figure 4.4 will reach a constant velocity when air resistance balances the sack's weight.

CHECK POINT

What net force does a sliding crate experience when you exert a force of 110 N and friction between the crate and the floor is 100 N?

Check Your Answer

10 N in the direction of your push (110 N – 100 N).

Mass and Weight

The acceleration imparted to an object depends not only on applied forces and friction forces but on the inertia of the object. How much inertia an object possesses depends on the amount of matter in the object—the more matter, the more inertia. In speaking of how much matter something has, we use the term *mass*. The greater the mass of an object, the greater its inertia. Mass is a measure of the inertia of a material object.

Mass corresponds to our intuitive notion of weight. We casually say that something has a lot of matter if it weighs a lot. But there is a difference between mass and weight. We can define each as follows:

Mass: ***The quantity of matter in an object. It is also the measure of the inertia or sluggishness that an object exhibits in response to any effort made to start it, stop it, or change its state of motion in any way.***

Weight: ***The force upon an object due to gravity.***

In the absence of acceleration, mass and weight are directly proportional to each other.[2] If the mass of an object is doubled, its weight is also doubled; if the mass is halved, the weight is halved. Because of this, mass and weight are often interchanged. Also, mass and weight are sometimes confused because it is customary to measure the quantity of matter in things (mass) by their gravitational attraction to Earth (weight). But mass is more fundamental than weight; it is a fundamental quantity that completely escapes the notice of most people.

There are times when weight corresponds to our unconscious notion of inertia. For example, if you are trying to determine which of two small objects is the heavier one, you might shake them back and forth in your hands or move them in some way instead of lifting them. In doing so, you are judging which of the two is more difficult to get moving, feeling which of the two is more resistant to a change in motion. You are really comparing the inertias of the objects.

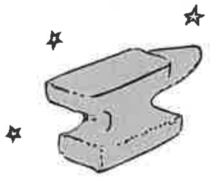

FIGURE 4.6

An anvil in outer space—between Earth and the Moon, for example—may be weightless, but it is not massless.

In the United States, the quantity of matter in an object is commonly described by the gravitational pull between it and Earth, or its *weight,* usually expressed in *pounds.* In most of the world, however, the measure of matter is commonly expressed in a mass unit, the kilogram. At the surface of Earth, a brick with a mass of 1 kilogram weighs 2.2 pounds. In metric units, the unit of force is the **newton,** which is equal to a little less than a quarter-pound (like the weight of a quarter-pound hamburger *after* it is cooked). A 1-kilogram brick weighs about 10 newtons

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[2] Weight and mass are directly proportional; weight = mg, where g is the constant of proportionality and has the value 10 N/kg (or more precisely, 9.8 N/kg). Equivalently, g is the acceleration due to gravity, 10 m/s^2 (the units N/kg are equivalent to m/s^2). In Chapter 9 we'll extend the definition of weight as the force that an object exerts on a supporting surface.

(more precisely, 9.8 N).[3] Away from Earth's surface, where the influence of gravity is less, a 1-kilogram brick weighs less. It would also weigh less on the surface of planets with less gravity than Earth. On the Moon's surface, for example, where the gravitational force on things is only 1/6 as strong as on Earth, a 1-kilogram brick weighs about 1.6 newtons (or 0.36 pounds). On planets with stronger gravity, it would weigh more, but the mass of the brick is the same everywhere. The brick offers the same resistance to speeding up or slowing down regardless of whether it's on Earth, on the Moon, or on any other body attracting it. In a drifting spaceship, where a scale with a brick on it reads zero, the brick still has mass. Even though it doesn't press down on the scale, the brick has the same resistance to a change in motion as it has on Earth. Just as much force would have to be exerted by an astronaut in the spaceship to shake it back and forth as would be required to shake it back and forth while on Earth. You'd have to provide the same amount of push to accelerate a huge truck to a given speed on a level surface on the Moon as on Earth. The difficulty of *lifting* it against gravity (weight), however, is something else. Mass and weight are different from each other (Figure 4.7).

FIGURE 4.7

The astronaut in space finds that it is just as difficult to shake the "weightless" anvil as it would be on Earth. If the anvil were more massive than the astronaut, which would shake more—the anvil or the astronaut?

A nice demonstration that distinguishes mass and weight is the massive ball suspended on the string, shown by David Yee in the Chapter 2 opener photo, and in Figure 4.8. The top string breaks when the lower string is pulled with a gradual increase in force, but the bottom string breaks when the lower string is jerked. Which of these cases illustrates the weight of the ball, and which illustrates the mass of the ball? Note that only the top string bears the weight of the ball. So, when the lower string is gradually pulled, the tension supplied by the pull is transmitted to the top string. The total tension in the top string is caused by the pull plus the weight of the ball. The top string breaks when the breaking point is reached. But, when the bottom string is jerked, the mass of the ball—its tendency to remain at rest—is responsible for the bottom string breaking.

FIGURE 4.8

Why will a slow, continuous increase in downward force break the string above the massive ball, while a sudden increase will break the lower string?

It is also easy to confuse mass and volume. When we think of a massive object, we often think of a big object. An object's size (volume), however, is not necessarily a good way to judge its mass. Which is easier to get moving: a car battery or an empty cardboard box of the same size? So, we find that mass is neither weight nor volume.

CHECK POINT

1. Does a 2-kg iron brick have twice as much *inertia* as a 1-kg iron brick? Twice as much *mass?* Twice as much *volume?* Twice as much *weight?*
2. Would it be easier to lift a cement truck on Earth's surface or to lift it on the Moon's surface?

Check Your Answers

1. The answers to all parts are *yes*.
2. A cement truck would be easier to lift on the Moon because the gravitational force is less on the Moon. When you *lift* an object, you are contending with the force of gravity (its weight). Although its mass is the same anywhere, its weight is only 1/6 as much on the Moon, so only 1/6 as much effort is required to lift it there. To move it horizontally, however, you are not pushing against gravity. When mass is the only factor, equal forces will produce equal accelerations, whether the object is on Earth or the Moon.

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[3] So 2.2 lb equal 9.8 N, or 1 N is approximately equal to 0.22 lb—about the weight of an apple. In the metric system it is customary to specify quantities of matter in units of mass (in grams or kilograms) and rarely in units of weight (in newtons). In the United States and countries that use the British system of units, however, quantities of matter are customarily specified in units of weight (in pounds). (The British unit of mass, the *slug,* is not well known.) See Appendix A for more about systems of measurement.

Mass Resists Acceleration

Push your friend on a skateboard and your friend accelerates. Now push equally hard on an elephant on a skateboard and the acceleration is much less. You'll see that the amount of acceleration depends not only on the force but on the mass being pushed. The same force applied to twice the mass produces half the acceleration; for three times the mass, one-third the acceleration. We say that, for a given force, the acceleration produced is inversely proportional to the mass. That is,

$$\text{Acceleration} \sim \frac{1}{\text{mass}}$$

By inversely we mean that the two values change in opposite directions. As the denominator increases, the whole quantity decreases. For example, the quantity 1/100 is less than 1/10.

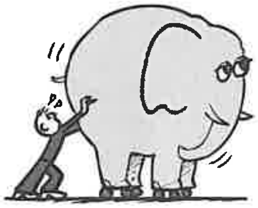

FIGURE 4.9

INTERACTIVE FIGURE

The greater the mass, the greater the force must be for a given acceleration.

FIGURE 4.10

An enormous force is required to accelerate this three-story-high earth mover when it carries a typical 350-ton load.

Newton's Second Law of Motion

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Newton's Second Law

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Newton's Second Law

Newton was the first to discover the relationship among three basic physical concepts—acceleration, force, and mass. He proposed one of the most important rules of nature, his second law of motion. Newton's second law states

> **The acceleration of an object is directly proportional to the net force acting on the object, is in the direction of the net force, and is inversely proportional to the mass of the object.**

In summarized form, this is

$$\text{Acceleration} \sim \frac{\text{net force}}{\text{mass}}$$

We use the wiggly line ~ as a symbol meaning "is proportional to." We say that acceleration a is directly proportional to the overall net force F and inversely proportional to the mass m. By this we mean that, if F increases, a increases by the same factor (if F doubles, a doubles); but if m increases, a decreases by the same factor (if m doubles, a is cut in half).

By using consistent units, such as newtons (N) for force, kilograms (kg) for mass, and meters per second squared (m/s^2) for acceleration, the proportionality may be

When two things are directly proportional to each other, as one increases, the other increases also. However, when two things are inversely proportional to each other, as one increases, the other decreases.

expressed as an exact equation:

$$\text{Acceleration} = \frac{\text{net force}}{\text{mass}}$$

In its briefest form, where a is acceleration, F_{net} is net force, and m is mass, it becomes

$$a = \frac{F_{\text{net}}}{m}$$

An object is accelerated in the direction of the force acting on it. Applied in the direction of the object's motion, a force will increase the object's speed. Applied in the opposite direction, it will decrease the speed of the object. Applied at right angles, it will deflect the object. Any other direction of application will result in a combination of speed change and deflection. *The acceleration of an object is always in the direction of the net force.*

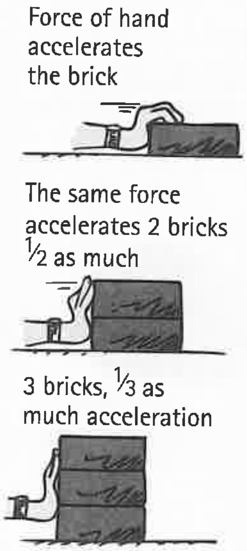

FIGURE 4.11

Acceleration is inversely proportional to mass.

CHECK POINT

1. In the previous chapter, acceleration was defined to be the time rate of change of velocity; that is, a = (change in v)/time. Are we in this chapter saying that acceleration is instead the ratio of force to mass; that is, $a = F/m$? Which is it?
2. A jumbo jet cruises at constant velocity of 1000 km/h when the thrusting force of its engines is a constant 100,000 N. What is the acceleration of the jet? What is the force of air resistance on the jet?

Check Your Answers

1. Acceleration is *defined* as the time rate of change of velocity and is *produced* by a force. How much force/mass (the cause) determines the rate change in v/time (the effect). So whereas we defined acceleration in Chapter 3, in this chapter we define the terms that produce acceleration.
2. The acceleration is zero because the velocity is constant. Since the acceleration is zero, it follows from Newton's second law that the net force is zero, which means that the force of air drag must just equal the thrusting force of 100,000 N and act in the opposite direction. So the air drag on the jet is 100,000 N. (Note that we don't need to know the velocity of the jet to answer this question. We need only to know that it is constant, our clue that acceleration and therefore net force is zero.)

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Free Fall Acceleration Explained

When Acceleration Is *g*—Free Fall

Although Galileo introduced both the concepts of inertia and acceleration, and although he was the first to measure the acceleration of falling objects, he could not explain *why* objects of various masses fall with equal accelerations. Newton's second law provides the explanation.

We know that a falling object accelerates toward Earth because of the gravitational force of attraction between the object and Earth. When the force of gravity is the only force—that is, when friction (such as air resistance) is negligible—we say that the object is in a state of free fall.

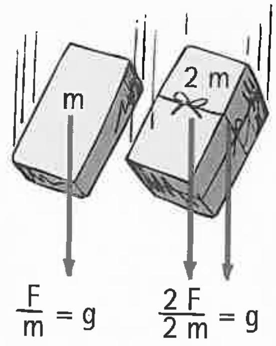

FIGURE 4.12

INTERACTIVE FIGURE

The ratio of weight (F) to mass (m) is the same for all objects in the same locality; hence, their accelerations are the same in the absence of air resistance.

The greater the mass of an object, the greater is the gravitational force of attraction between it and Earth. The double brick in Figure 4.12, for example, has twice the gravitational attraction of the single brick. Why, then, as Aristotle supposed, doesn't the double brick fall twice as fast? The answer is that the acceleration of an object depends not only on the force—in this case, the weight—but also on the object's resistance to motion, its inertia. Whereas a force produces an acceleration,

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- We see in free fall that weight/mass = g. So we can say that weight = mg.

inertia is a *resistance* to acceleration. So twice the force exerted on twice the inertia produces the same acceleration as half the force exerted on half the inertia. Both accelerate equally. The acceleration due to gravity is symbolized by g. We use the symbol g, rather than a, to denote that acceleration is due to gravity alone.

The ratio of weight to mass for freely falling objects equals a constant—g. This is similar to the constant ratio of circumference to diameter for circles, which equals the constant π (Figure 4.13).

We now understand that the acceleration of free fall is independent of an object's mass. A boulder 100 times more massive than a pebble falls with the same acceleration as the pebble because, although the force on the boulder (its weight) is 100 times greater than the force on the pebble, its resistance to a change in motion (its mass) is 100 times that of the pebble. The greater force offsets the equally greater mass.

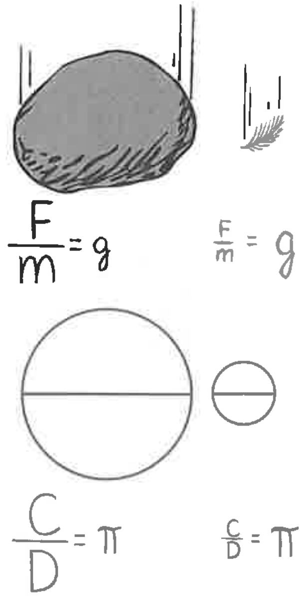

FIGURE 4.13

The ratio of weight (F) to mass (m) is the same for the large rock and the small feather; similarly, the ratio of circumference (C) to diameter (D) is the same for the large and the small circle.

CHECK POINT

In a vacuum, a coin and a feather fall at the same rate, side by side. Would it be correct to say that equal forces of gravity act on both the coin and the feather when in a vacuum?

Check Your Answer

No, no, no, a thousand times no! These objects accelerate equally not because the forces of gravity on them are equal, but because the *ratios* of their weights to their masses are equal. Although air resistance is not present in a vacuum, gravity is. (You'd know this if you stuck your hand into a vacuum chamber and the truck shown in Figure 4.10 rolled over it!) If you answered *yes* to this question, let this be a warning to be more careful when you think physics!

When Acceleration Is Less Than g—Nonfree Fall

Objects falling in a vacuum are one thing, but what of the practical cases of objects falling in air? Although a feather and a coin will fall equally fast in a vacuum, they fall quite differently in air. How do Newton's laws apply to objects falling in air? The answer is that Newton's laws apply for *all* objects, whether freely falling or falling in the presence of resistive forces. The accelerations, however, are quite different for the two cases. The important thing to keep in mind is the idea of *net force*. In a vacuum or in cases in which air resistance can be neglected, the net force is the weight because it is the only force. In the presence of air resistance, however, the net force is less than the weight—it is the weight minus air drag, the force arising from air resistance.[4]

When Galileo tried to explain why all objects fall with equal accelerations, wouldn't he have loved to know the rule $a = F/m$?

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[4] In mathematical notation,

$$a = \frac{F_{\text{net}}}{m} = \frac{mg - R}{m}$$

where mg is the weight and R is the air resistance. Note that when $R = mg$, $a = 0$; then, with no acceleration, the object falls at constant velocity. With elementary algebra we can go another step and get

$$a = \frac{F_{\text{net}}}{m} = \frac{mg - R}{m} = g - \frac{R}{m}$$

We see that the acceleration a will always be less than g if air resistance R impedes falling. Only when $R = 0$ does $a = g$.

The force of air drag experienced by a falling object depends on two things. First, it depends on the frontal area of the falling object—that is, on the amount of air the object must plow through as it falls. Second, it depends on the speed of the falling object; the greater the speed, the greater the number of air molecules an object encounters per second and the greater the force of molecular impact. Air drag depends on the size and the speed of a falling object.

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Falling and Air Resistance

In some cases, air drag greatly affects falling; in other cases, it doesn't. Air drag is important for a falling feather. Because a feather has so much area for an object so light in weight, it doesn't have to fall very fast before the upward-acting air resistance cancels the downward-acting weight. The net force on the feather is then zero and acceleration terminates. When acceleration terminates, we say that the object has reached its **terminal speed.** If we are concerned with direction, down for falling objects, we say the object has reached its terminal velocity. The same idea applies to all objects falling in air. Consider skydiving. As a falling skydiver gains speed, air drag may finally build up until it equals the weight of the skydiver. If and when this happens, the *net force* becomes zero and the skydiver no longer accelerates; she has reached her terminal velocity. For a feather, terminal velocity is a few centimeters per second, whereas, for a skydiver, it is about 200 kilometers per hour. A skydiver may vary this speed by varying position. Head or feet first is a way of encountering less air and thus less air drag and attaining maximum terminal velocity. A smaller terminal velocity is attained by spreading oneself out like a flying squirrel.

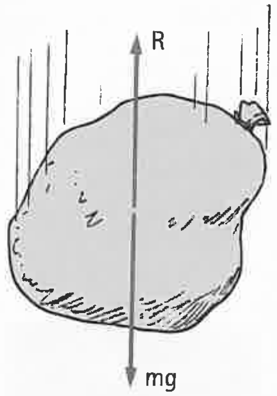

FIGURE 4.14

When weight mg is greater than air resistance R, the falling sack of mail accelerates. At higher speeds, R increases. When $R = mg$, acceleration reaches zero, and the sack reaches its terminal velocity.

Terminal velocities are very much less if the skydiver wears a wingsuit, as shown in the center opening photo at the beginning of this chapter. The wingsuit not only increases the frontal area of the diver, but provides a lift similar to that achieved by flying squirrels when they fashion their bodies into "wings." This new and exhilarating sport, *wingsuit flying,* goes beyond what flying squirrels can accomplish, for a wingsuit flyer can achieve horizontal speeds of more than 160 km/h (100 mph). Looking more like flying bullets than flying squirrels, high-performance wingsuits allow these "bird people" to glide with remarkable precision. To land safely, parachutes are deployed. Projects to land without a parachute, however, are underway.

The large frontal area provided by a parachute produces low terminal speeds for safe landings. To understand the physics of a parachute, consider a man and woman parachuting together from the same altitude (Figure 4.15). Suppose that the man is twice as heavy as the woman and that their same-sized parachutes are initially opened. Having parachutes of the same size means that, at equal speeds, the air resistance is the same on both of them. Who reaches the ground first—the heavy man or the lighter woman? The answer is that the person who falls faster gets to the ground first—that is, the person with the greatest terminal speed. At first we might think that, because the parachutes are the same, the terminal speeds for each would be the same and, therefore, that both would reach the ground at the same time. This doesn't happen, however, because air drag depends on speed. Greater speed means greater force of air impact. The woman will reach her terminal speed when the air drag against her parachute equals her weight. When this occurs, the air drag against the parachute of the man will not yet equal his weight. He must fall faster than she does for the air drag to match his greater weight.[5] Terminal velocity is greater for the heavier person, with the result that the heavier person reaches the ground first.

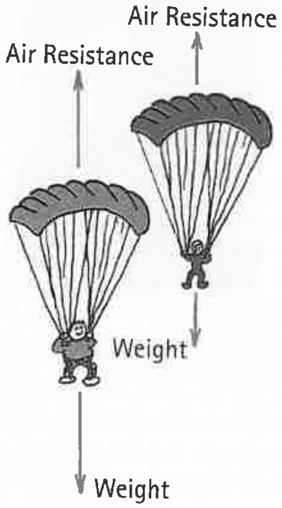

FIGURE 4.15

The heavier parachutist must fall faster than the lighter parachutist for air resistance to cancel his greater weight.

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[5] Terminal speed for the twice-as-heavy man will be about 41% greater than the woman's terminal speed, because the retarding force of air resistance is proportional to speed squared. ($v_{\text{man}}^2/v_{\text{woman}}^2 = 1.41^2 = 2$.)

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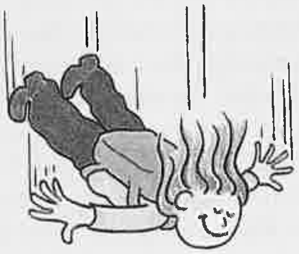
- Headfirst, with arms tucked in, skydivers can reach terminal speeds of about 180 km/h (110 mph). Terminal speeds are less with a wingsuit, and greatly reduced with a parachute.

CHECK POINT

Nellie Newton skydives from a high-flying helicopter. As she falls faster and faster through the air, does her acceleration increase, decrease, or remain the same?



Check Your Answer

Acceleration decreases because the net force on Nellie decreases. Net force is equal to her weight minus her air resistance, and since air resistance increases with increasing speed, net force and hence acceleration decrease. By Newton's second law,

$$a = \frac{f_{\text{net}}}{m} = \frac{mg - R}{m}$$

where mg is her weight and R is the air resistance she encounters. As R increases, a decreases. Note that if she falls fast enough so that $R = mg$, $a = 0$, then with no acceleration she falls at constant speed.

Consider a pair of tennis balls, one a regular hollow ball and the other filled with iron pellets. Although they are the same size, the iron-filled ball is considerably heavier than the regular ball. If you hold them above your head and drop them simultaneously, you'll see that they strike the ground at about the same time. But if you drop them from a greater height—say, from the top of a building—you'll note the heavier ball strikes the ground first. Why? In the first case, the balls do not gain much speed in their short fall. The air drag they encounter is small compared with their weights, even for the regular ball. The tiny difference in their arrival time is not noticed. But, when they are dropped from a greater height, the greater speeds of fall are met with greater air resistance. At any given speed, each ball encounters the same air resistance because each has the same size. This same air resistance may be a lot compared with the weight of the lighter ball, but only a little compared with the weight of the heavier ball (like the parachutists in Figure 4.15). For example, 1 N of air drag acting on a 2-N object will reduce its acceleration by half, but 1 N of air drag on a 200-N object will only slightly diminish its acceleration. So, even with equal air resistances, the accelerations of each are different. There is a moral to be learned here. Whenever you consider the acceleration of something, use the equation of Newton's second law to guide your thinking: The acceleration is equal to the ratio of *net* force to the mass. For the falling tennis balls, the net force on the hollow ball is appreciably reduced as air drag builds up, while the net force on the iron-filled ball is only slightly reduced. Acceleration decreases as net force decreases, which, in turn, decreases as air drag increases. If and when the air drag builds up to equal the weight of the falling object, then the net force becomes zero and acceleration terminates.

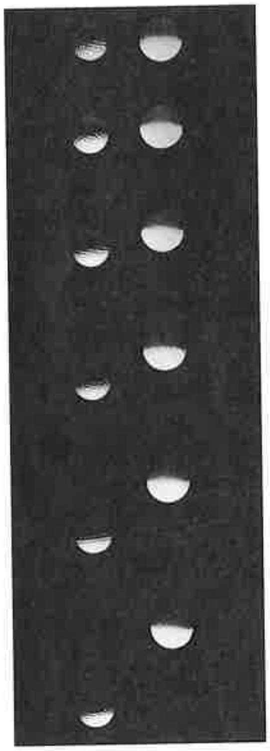


FIGURE 4.16

A stroboscopic study of a golf ball (left) and a Styrofoam ball (right) falling in air. The air resistance is negligible for the heavier golf ball, and its acceleration is nearly equal to g. Air resistance is not negligible for the lighter Styrofoam ball, which reaches its terminal velocity sooner.

SUMMARY OF TERMS

Force Any influence that can cause an object to be accelerated, measured in newtons (or in pounds, in the British system).

Friction The resistive force that opposes the motion or attempted motion of an object either past another object with which it is in contact or through a fluid.

Mass The quantity of matter in an object. More specifically, it is the measure of the inertia or sluggishness that an object exhibits in response to any effort made to start it, stop it, deflect it, or change in any way its state of motion.

Weight The force due to gravity on an object (mg).

Volume The quantity of space an object occupies.

Newton's second law The acceleration of an object is directly proportional to the net force acting on the object, is in the direction of the net force, and is inversely proportional to the mass of the object.

Newton The SI unit of force. One newton (symbol N) is the force that will give an object of mass 1 kg an acceleration of 1 m/s^2.

Kilogram The fundamental SI unit of mass. One kilogram (symbol kg) is the mass of 1 liter (1 L) of water at 4 C°.

Free fall Motion under the influence of gravitational pull only.

Terminal speed The speed at which the acceleration of a falling object terminates because air resistance balances its weight. When direction is specified, then we speak of **terminal velocity.**

SUMMARY OF EQUATIONS

Weight $= mg$

Acceleration: $a = \dfrac{F_{\text{net}}}{m}$

Force $= ma$

REVIEW QUESTIONS

Force Causes Acceleration

1. Is acceleration proportional to net force, or does acceleration equal net force?

Friction

2. How does friction affect the net force on an object?
3. How great is the force of friction compared with your push on a crate that doesn't move on a level floor?
4. As you increase your push, will friction on the crate increase also?
5. Once the crate is sliding, how hard do you push to keep it moving at constant velocity?
6. Which is normally greater, static friction or sliding friction on the same object?
7. How does the force of friction for a sliding object vary with speed?
8. Slide a block on its widest surface, then tip the block so it slides on its narrowest surface. In which case is friction greater?
9. Does fluid friction vary with speed? With area of contact?

Mass and Weight

10. What relationship does mass have with inertia?
11. What relationship does mass have with weight?
12. Which is more fundamental, *mass* or *weight*? Which varies with location?
13. Fill in the blanks: Shake something to and fro and you're measuring its ______. Lift it against gravity and you're measuring its ______.
14. Fill in the blanks: The Standard International unit for mass is the ______. The Standard International unit for force is the ______.
15. What is the approximate weight of a quarter-pound hamburger after it is cooked?
16. What is the weight of a 1-kilogram brick?
17. In the string-pull illustration in Figure 4.8, a gradual pull of the lower string results in the top string breaking. Does this illustrate the ball's weight or its mass?
18. In the string-pull illustration in Figure 4.8, a sharp jerk on the bottom string results in the bottom string breaking. Does this illustrate the ball's weight or its mass?
19. Clearly distinguish among *mass, weight*, and *volume.*
20. Is acceleration *directly* proportional to mass, or is it *inversely* proportional to mass? Give an example.

Newton's Second Law of Motion

21. State Newton's second law of motion.
22. If we say that one quantity is *directly proportional* to another quantity, does this mean they are *equal* to each other? Explain briefly, using mass and weight as an example.
23. If the net force acting on a sliding block is somehow tripled, by how much does the acceleration increase?
24. If the mass of a sliding block is tripled while a constant net force is applied, by how much does the acceleration decrease?
25. If the mass of a sliding block is somehow tripled at the same time the net force on it is tripled, how does the resulting acceleration compare with the original acceleration?
26. How does the direction of acceleration compare with the direction of the net force that produces it?

When Acceleration Is g—Free Fall

27. What is meant by *free fall*?
28. The ratio of circumference to diameter for all circles is π. What is the ratio of force to mass for freely falling bodies?
29. Why doesn't a heavy object accelerate more than a light object when both are freely falling?

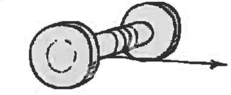
When Acceleration Is Less Than g—Nonfree Fall

30. What is the net force that acts on a 10-N freely falling object?
31. What is the net force that acts on a 10-N falling object when it encounters 4 N of air resistance? 10 N of air resistance?

32. What two principal factors affect the force of air resistance on a falling object?
33. What is the acceleration of a falling object that has reached its terminal velocity?
34. Why does a heavy parachutist fall faster than a lighter parachutist who wears a parachute of the same size?
35. If two objects having the same size fall through air at different speeds, which encounters the greater air resistance?

PROJECT

1. Write a letter to Grandma, similar to the one of Project 1 in Chapter 3. Tell her that Galileo introduced the concepts of acceleration and inertia and was familiar with forces but didn't see the connection among these three concepts. Tell her how Isaac Newton did see the connection and how it explains why heavy and light objects in free fall gain the same speed in the same time. In this letter, it's okay to use an equation or two, as long as you make it clear to Grandma that an equation is a shorthand notation of ideas you've explained.
2. Drop a sheet of paper and a coin at the same time. Which reaches the ground first? Why? Now crumple the paper into a small, tight wad and again drop it with the coin. Explain the difference observed. Will they fall together if dropped from a second-, third-, or fourth-story window? Try it and explain your observations.
3. Drop a book and a sheet of paper, and note that the book has a greater acceleration—g. Place the paper beneath the book so that it is forced against the book as both fall, so both fall at g. How do the accelerations compare if you place the paper on top of the raised book and then drop both? You may be surprised, so try it and see. Then explain your observation.
4. Drop two balls of different weight from the same height, and, at small speeds, they practically fall together. Will they roll together down the same inclined plane? If each is suspended from an equal length of string, making a pair of pendulums, and displaced through the same angle, will they swing back and forth in unison? Try it and see; then explain using Newton's laws.
5. The net force acting on an object and the resulting acceleration are always in the same direction. You can demonstrate this with a spool. If the spool is gently pulled horizontally to the right, in which direction will it roll?



PLUG AND CHUG

Make these simple one-step calculations and familiarize yourself with the equations that link the concepts of force, mass, and acceleration.

Weight $= mg$

1. Calculate the weight in newtons of a person having a mass of 50 kg.
2. Calculate the weight in newtons of a 2000-kg elephant.
3. Calculate the weight in newtons of a 2.5-kg melon. What is its weight in pounds?
4. An apple weighs about 1 N. What is its mass in kilograms? What is its weight in pounds?
5. Susie Small finds that she weighs 300 N. Calculate her mass.

Acceleration: $a = \dfrac{F_{\text{net}}}{m}$

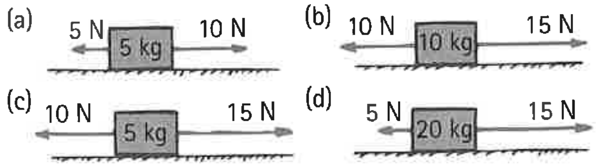
6. Calculate the acceleration of a 2000-kg, single-engine airplane just before takeoff when the thrust of its engine is 500 N.
7. Calculate the acceleration of a 300,000-kg jumbo jet just before takeoff when the thrust on the aircraft is 120,000 N.
8. (a) Calculate the acceleration of a 2-kg block on a horizontal friction-free air table when you exert a horizontal net force of 20 N. (b) What acceleration occurs if the friction force is 4 N?

Force $= ma$

9. Calculate the horizontal force that must be applied to a 1-kg puck to make it accelerate on a horizontal friction-free air table with the same acceleration it would have if it were dropped and fell freely.
10. Calculate the horizontal force that must be applied to produce an acceleration of 1.8 g for a 1.2-kg puck on a horizontal friction-free air table.

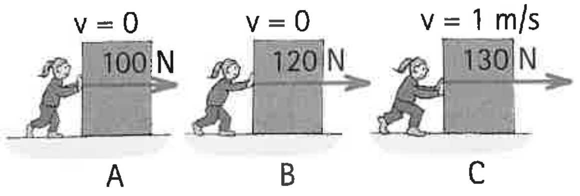
RANKING

1. Boxes of various masses are on a friction-free, level table. From greatest to least, rank the

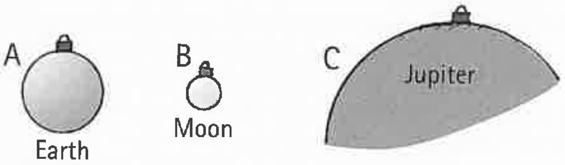


a. net forces on the boxes.
b. accelerations of the boxes.

2. In all three cases, A, B, and C, the crate is in equilibrium (no acceleration). From greatest to least, rank the amount of friction between the crate and the floor.

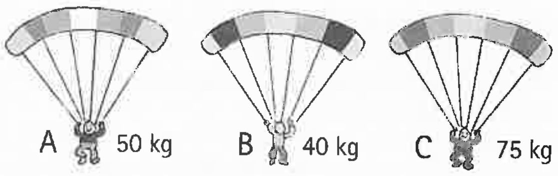


3. Consider a 100-kg box of tools in the locations A, B, and C. From greatest to least, rank the



a. masses of the 100-kg box of tools.
b. weights of the 100-kg box of tools.

4. Three parachutists, A, B, and C, each have reached terminal velocity at the same distance above the ground below.

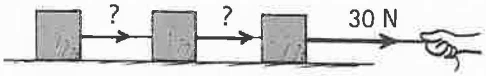


a. From fastest to slowest, rank the amount of their terminal velocities.
b. From longest to shortest times, rank their order in reaching the ground.

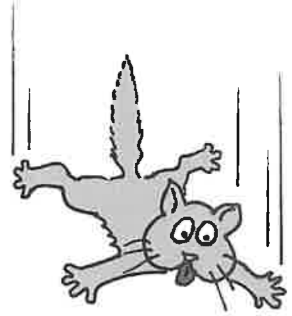
EXERCISES

1. Can the velocity of an object reverse direction while maintaining a constant acceleration? If so, give an example; if not, provide an explanation.
2. On a long alley, a bowling ball slows down as it rolls. Is any horizontal force acting on the ball? How do you know?
3. Is it possible to move in a curved path in the absence of a force? Defend your answer.
4. An astronaut tosses a rock on the Moon. What force(s) act(s) on the rock during its curved path?
5. Since an object weighs less on the surface of the Moon than on Earth's surface, does it have less inertia on the Moon's surface?
6. Which contains more apples, a 1-pound bag of apples on Earth or a 1-pound bag of apples on the Moon? Which contains more apples, a 1-kilogram bag of apples on Earth or a 1-kilogram bag of apples on the Moon?
7. A crate remains at rest on a factory floor while you push on it with a horizontal force *F*. How big is the friction force exerted on the crate by the floor? Explain.
8. A 400-kg bear grasping a vertical tree slides down at constant velocity. What is the friction force that acts on the bear?
9. In an orbiting space shuttle, you are handed two identical boxes, one filled with sand and the other filled with feathers. How can you determine which is which without opening the boxes?
10. Your empty hand is not hurt when it bangs lightly against a wall. Why does it hurt if you're carrying a heavy load? Which of Newton's laws is most applicable here?
11. Why is a massive cleaver more effective for chopping vegetables than an equally sharp knife?
12. Does the mass of an astronaut change when he or she is visiting the International Space Station? Defend your answer.
13. When a junked car is crushed into a compact cube, does its mass change? Its weight? Explain.
14. Gravity on the surface of the Moon is only 1/6 as strong as gravity on Earth. What is the weight of a 10-kg object on the Moon and on Earth? What is its mass on each?
15. Does a dieting person more accurately lose mass or lose weight?
16. What weight change occurs when your mass increases by 2 kg?
17. What is your own mass in kilograms? Your weight in newtons?
18. A grocery bag can withstand 300 N of force before it rips apart. How many kilograms of apples can it safely hold?
19. Consider a heavy crate resting on the bed of a flatbed truck. When the truck accelerates, the crate also accelerates and remains in place. Identify the force that accelerates the crate.
20. Explain how Newton's first law of motion can be considered to be a consequence of Newton's second law.
21. When a car is moving in reverse, backing from a driveway, the driver applies the brakes. In what direction is the car's acceleration?
22. The auto in the sketch moves forward as the brakes are applied. A bystander says that during the interval of braking, the auto's velocity and acceleration are in opposite directions. Do you agree or disagree?

23. Aristotle claimed that the speed of a falling object depends on its weight. We now know that objects in free fall, whatever their weights, undergo the same gain in speed. Why does weight not affect acceleration?
24. When blocking in football, a defending lineman often attempts to get his body under the body of his opponent and push upward. What effect does this have on the friction force between the opposing lineman's feet and the ground?
25. A race car travels along a raceway at a constant velocity of 200 km/h. What horizontal net force acts on the car?
26. Three identical blocks are pulled, as shown, on a horizontal frictionless surface. If tension in the rope held by the hand is 30 N, what is the tension in the other ropes?



27. To pull a wagon across a lawn with constant velocity, you have to exert a steady force. Reconcile this fact with Newton's first law, which says that motion with constant velocity requires no force.
28. Free fall is motion in which gravity is the only force acting. (a) Is a skydiver who has reached terminal speed in free fall? (b) Is a satellite above the atmosphere that circles Earth in free fall?
29. When a coin is tossed upward, what happens to its velocity while ascending? Its acceleration? (Neglect air resistance.)
30. How much force acts on a tossed coin when it is halfway to its maximum height? How much force acts on it when it reaches its peak? (Neglect air resistance.)
31. Sketch the path of a ball tossed vertically into the air. (Neglect air resistance.) Draw the ball halfway to the top, at the top, and halfway down to its starting point. Draw a force vector on the ball in all three positions. Is the vector the same or different in the three locations? Is the acceleration the same or different in the three locations?
32. As you leap upward in a standing jump, how does the force that you exert on the ground compare with your weight?
33. When you jump vertically off the ground, what is your acceleration when you reach your highest point?
34. What is the acceleration of a rock at the top of its trajectory when it has been thrown straight upward? (Is your answer consistent with Newton's second law?)
35. A common saying goes, "It's not the fall that hurts you; it's the sudden stop." Translate this into Newton's laws of motion.
36. A friend says that, as long as a car is at rest, no forces act on it. What do you say if you're in the mood to correct the statement of your friend?
37. When your car moves along the highway at constant velocity, the net force on it is zero. Why, then, do you have to keep running your engine?
38. What is the net force on a 1-N apple when you hold it at rest above your head? What is the net force on it after you release it?
39. A "shooting star" is usually a grain of sand from outer space that burns up and gives off light as it enters the atmosphere. What exactly causes this burning?
40. Does a stick of dynamite contain force?
41. A parachutist, after opening her parachute, finds herself gently floating downward, no longer gaining speed. She feels the upward pull of the harness, while gravity pulls her down. Which of these two forces is greater? Or are they equal in magnitude?
42. Does a falling object increase in speed if its acceleration of fall decreases?
43. What is the net force acting on a 1-kg ball in free fall?
44. What is the net force acting on a falling 1-kg ball if it encounters 2 N of air resistance?
45. A friend says that, before the falling ball in the previous exercise reaches terminal velocity, it *gains* speed while acceleration *decreases*. Do you agree or disagree with your friend? Defend your answer.
46. Why will a sheet of paper fall more slowly than one that is wadded into a ball?
47. Upon which will air resistance be greater—a sheet of falling paper or the same paper wadded into a ball that falls at a faster terminal speed? (Careful!)
48. Hold a Ping-Pong ball and a golf ball at arm's length and drop them simultaneously. You'll see them hit the floor at about the same time. But, if you drop them off the top of a high ladder, you'll see the golf ball hit first. What is your explanation?
49. How does the force of gravity on a raindrop compare with the air drag it encounters when it falls at constant velocity?
50. If you hold your book horizontally with a piece of paper beneath it, then drop both, they fall together. Repeat, but this time place the paper on *top* of the book. Describe the motion of the paper relative to the book. (Try it and see!)
51. When a parachutist opens her parachute after reaching terminal speed, in what direction does she accelerate?
52. How does the terminal speed of a parachutist before opening a parachute compare to terminal speed after? Why is there a difference?
53. How does the gravitational force on a falling body compare with the air resistance it encounters before it reaches terminal velocity? After reaching terminal velocity?
54. Why is it that a cat that accidentally falls from the top of a 50-story building hits a safety net below no faster than if it fell from the twentieth story?

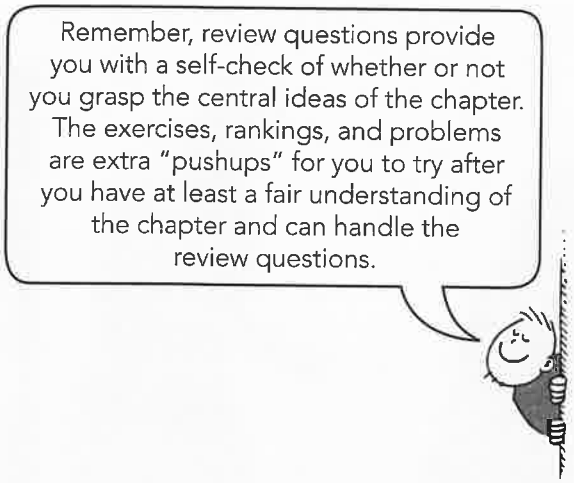


55. Under what conditions would a metal sphere dropping through a viscous liquid be in equilibrium?
56. When and if Galileo dropped two balls from the top of the Leaning Tower of Pisa, air resistance was not really negligible. Assuming that both balls were of the same size, one made of wood and one of metal, which ball actually struck the ground first? Why?
57. If you drop a pair of tennis balls simultaneously from the top of a building, they will strike the ground at the same time. If you fill one of the balls with lead pellets and then drop them together, which one will hit the ground first? Which one will experience greater air resistance? Defend your answers.
58. In the absence of air resistance, if a ball is thrown vertically upward with a certain initial speed, on returning to its original level it will have the same speed. When air resistance is a factor, will the ball be moving faster, the same, or more slowly than its throwing speed when it gets back to the same level? Why? (Physicists often use a "principle of exaggeration" to help them analyze a problem. Consider the exaggerated case of a feather, not a ball, because the effect of air resistance on the feather is more pronounced and therefore easier to visualize.)
59. If a ball is thrown vertically into the air in the presence of air resistance, would you expect the time during which it rises to be longer or shorter than the time during which it falls? (Again use the "principle of exaggeration.")
60. Make up two multiple-choice questions that would check a classmate's understanding of the distinction between mass and weight.

PROBLEMS

1. One pound is the same as 4.45 newtons. What is the weight in pounds of 1 newton?
2. If your friend Katelyn weighs 500 N, what is her weight in pounds?
3. Consider a 40-kg block of cement that is pulled sideways with a net force of 200 N. Show that its acceleration is 5 m/s^2.
4. Consider a mass of 1 kg accelerated 1 m/s^2 by a force of 1 N. Show that the acceleration would be the same for a force of 2 N acting on 2 kg.
5. Consider a business jet of mass 30,000 kg in takeoff when the thrust for each of two engines is 30,000 N. Show that its acceleration is 2 m/s^2.
6. Leroy, who has a mass of 100 kg, is skateboarding at 9.0 m/s when he smacks into a brick wall and comes to a dead stop in 0.2 s.
   a. Show that his deceleration is 45 m/s^2.
   b. Show that the force of impact is 4500 N. (ouch!)

• 7. A rock band's tour bus, mass *M*, is accelerating away from a STOP sign at rate *a* when a piece of heavy metal, mass *M*/6, falls onto the top of the bus and remains there.
   a. Show that the bus's acceleration is now $\frac{6}{7}a$.
   b. If the initial acceleration of the bus is 1.2 m/s^2, show that when the bus carries the heavy metal with it, the acceleration will be 1.0 m/s^2.



CHAPTER 4 ONLINE RESOURCES

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- Newton's Second Law

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- Friction
- Newton's Second Law
- Free-Fall Acceleration Explained
- Falling and Air Resistance

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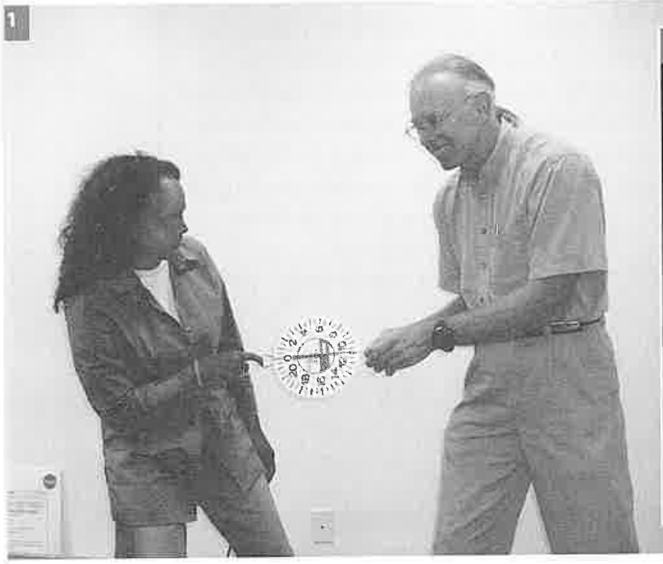
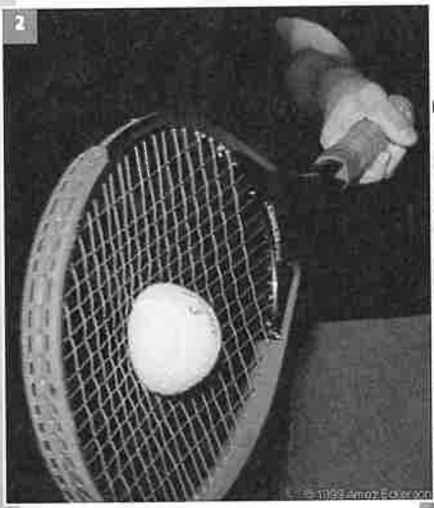
5 Newton's Third Law of Motion





1 Darlene Librero pulls with one finger; Paul Doherty pulls with both hands. Who exerts more force on the scale? 2 Does the racquet hit the ball or does the ball hit the racquet? Answer: The racquet cannot hit the ball *unless* the ball simultaneously hits the racquet—that's the law! 3 Wife Lil and I demonstrate Newton's third law— that you cannot touch without being touched.

When Isaac Newton was 26 years old he was appointed the Lucasian Professor of Mathematics at Trinity College in Cambridge. He had personal conflicts with the religious positions of the College, namely questioning the idea of the Trinity as a foundational tenet of Christianity at that time. At the age of 46, his energies turned somewhat from science when he was elected to a 1-year term as a member of Parliament. (At 57, he was elected to a second term.) In his two years in Parliament, he never gave a speech. One day he rose and the House fell silent to hear the great man. Newton's "speech" was very brief; he simply requested that a window be closed because of a draft.

A further turn from his work in science was his appointment as warden, and then as master, of the mint. Newton resigned his professorship and directed his efforts toward greatly improving the workings of the mint, to the dismay of counterfeiters who were then flourishing. He maintained his membership in the Royal Society and at age 60 was elected president, then was reelected each year for the rest of his life.

Although Newton's hair turned gray at age 30, it remained full, long, and wavy all his life, and, unlike others in his time, he did not wear a wig. He was a modest man, overly sensitive to criticism, and he never married. He remained healthy in body and mind into old age. At 80, he still had all his teeth, his eyesight and hearing were sharp, and his mind was alert. In his lifetime he was regarded by his countrymen as the greatest scientist who ever lived. In 1705, he was knighted by Queen Anne. Newton died at the age of 84 and was buried in Westminster Abbey along with England's monarchs and heroes. His laws of motion were all that was needed 242 years later to put humans on the Moon. This chapter presents the third of his three laws of motion.

Forces and Interactions

So far we've treated force in its simplest sense—as a push or pull. Yet no push or pull ever occurs alone. Every force is part of an *interaction* between one thing and another. When you push on a wall with your fingers, more is happening than your push on the wall. You're interacting with the wall, which also pushes back on you. This is evident in your bent fingers, as illustrated in Figure 5.1. There is a pair of forces involved: your push on the wall and the wall pushes back on you. These forces are equal in magnitude (have the same strength) and opposite in direction, and they constitute a single interaction. In fact, you can't push on the wall *unless* the wall pushes back.[1]

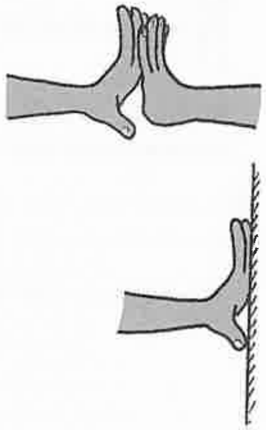


FIGURE 5.1

INTERACTIVE FIGURE

You can feel your fingers being pushed by your friend's fingers. You also feel the same amount of force when you push on a wall and it pushes back on you. As a point of fact, you can't push on the wall *unless* it pushes back on you!

Consider a boxer's fist hitting a massive punching bag. The fist hits the bag (and dents it) while the bag hits back on the fist (and stops its motion). A pair of forces is involved in hitting the bag. The force pair can be quite large. But what of hitting a piece of tissue paper, as discussed earlier? The boxer's fist can only exert as much force on the tissue paper as the tissue paper can exert on the fist. Furthermore, the fist can't exert any force at all unless what is being hit exerts the same amount of force back. An interaction requires a *pair* of forces acting on *two* separate objects.

FIGURE 5.2

When you lean against a wall, you exert a force on the wall. The wall simultaneously exerts an equal and opposite force on you. Hence you don't topple over.

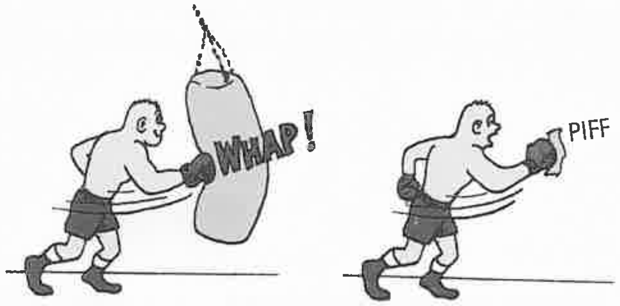


FIGURE 5.3

He can hit the massive bag with considerable force. But with the same punch he can exert only a tiny force on the tissue paper in midair.

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Video
Forces and Interaction

Other examples: You pull on a rope attached to a cart, acceleration occurs. When doing so, the cart pulls back on you, as evidenced perhaps by the tightening of the rope wrapped around your hand. A hammer hits a stake and drives it into the ground. In doing so, the stake exerts an equal amount of force on the hammer, which brings the hammer to an abrupt halt. One thing interacts with another—you with the cart, or the hammer with the stake.

Which exerts the force and which receives the force? Isaac Newton's response was that neither force has to be identified as "exerter" or "receiver"; he concluded that both objects must be treated equally. For example, when you pull the cart, the cart pulls on you. This pair of forces, your pull on the cart and the cart's pull on you, makes up the single interaction between you and the cart. In the interaction between the hammer and the stake, the hammer exerts a force against the stake but is itself brought to a halt in the process. Such observations led Newton to his third law of motion.

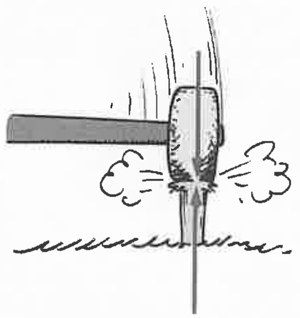

FIGURE 5.4

In the interaction between the hammer and the stake, each exerts the same amount of force on the other.

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[1] We tend to think that only living things are capable of pushing and pulling. But inanimate things can do the same. So please don't be troubled about the idea of the inanimate wall pushing on you. It does, just as another person leaning against you would.

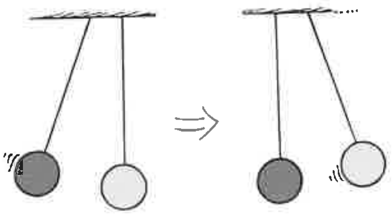

FIGURE 5.5
The impact forces between the blue ball and the yellow ball move the yellow ball and stop the blue ball.

Newton's Third Law of Motion

Newton's third law states:

> **Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first.**

We can call one force the *action force* and the other the *reaction force.* Then we can express Newton's third law in the form:

> **To every action there is always an opposed equal reaction.**

It doesn't matter which force we call *action* and which we call *reaction.* The important thing is that they are co-parts of a single interaction and that neither force exists without the other.

When you walk, you interact with the floor. You push against the floor, and the floor pushes against you. The pair of forces occurs at the same time (they are *simultaneous*). Likewise, the tires of a car push against the road while the road pushes back on the tires—the tires and road simultaneously push against each other. In swimming, you interact with the water, pushing the water backward, while the water simultaneously pushes you forward—you and the water push against each other. The reaction forces are what account for our motion in these examples. These forces depend on friction; a person or car on ice, for example, may be unable to exert the action force to produce the needed reaction force. Forces occur in *force pairs.* Neither force exists without the other.

FIGURE 5.6
In the interaction between the car and the truck, is the force of impact the same on each? Is the damage the same?

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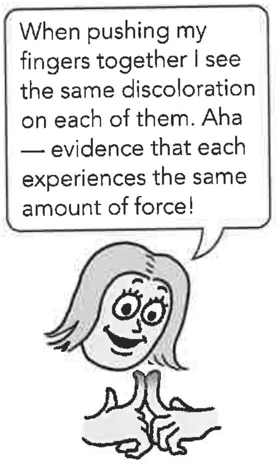
Tutorial
Newton's Third Law



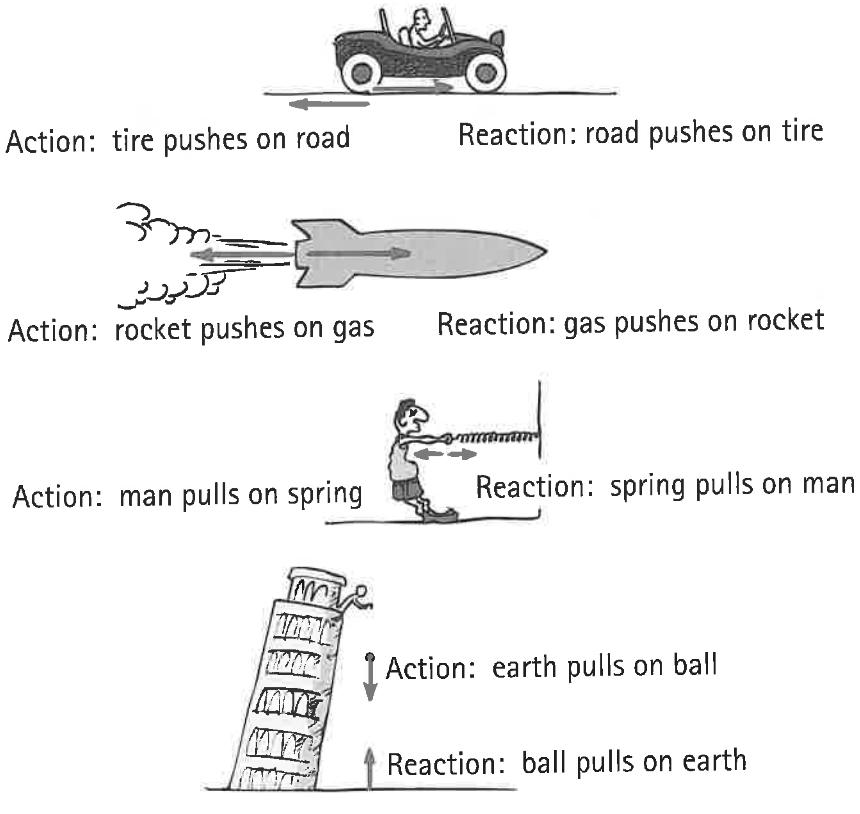


FIGURE 5.7
Action and reaction forces. Note that when action is "*A* exerts force on *B*," the reaction is then simply "*B* exerts force on *A*."

CHECK POINT

Does a speeding missile possess force?

Check Your Answer

No, a force is not something an object *has*, like mass, but is part of an interaction between one object and another. A speeding missile may possess the capability of exerting a force on another object when interaction occurs, but it does not possess force as a thing in itself. As we will see in the following chapters, a speeding missile possesses momentum and kinetic energy.

DEFINING YOUR SYSTEM

An interesting question often arises: Since action and reaction forces are equal and opposite, why don't they cancel to zero? To answer this question, we must consider the *system* involved. Consider, for example, a system consisting of a single orange, Figure 5.8. The dashed line surrounding the orange encloses and defines the system. The vector that pokes outside the dashed line represents an external force on the system. The system accelerates in accord with Newton's second law. In Figure 5.9, we see that this force is provided by an apple, which doesn't change our analysis. The apple is outside the system. The fact that the orange simultaneously exerts a force on the apple, which is external to the system, may affect the apple (another system), but not the orange. You can't cancel a force on the orange with a force on the apple. So, in this case, the action and reaction forces don't cancel.

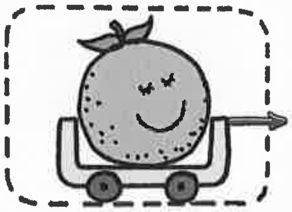


FIGURE 5.8

INTERACTIVE FIGURE

A force acts on the orange, and the orange accelerates to the right.

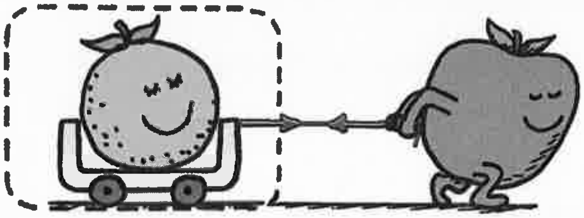


FIGURE 5.9

INTERACTIVE FIGURE

The force on the orange, provided by the apple, is not cancelled by the reaction force on the apple. The orange still accelerates.

A system may be as tiny as an atom or as large as the universe.

Now let's consider a larger system, enclosing *both* the orange and the apple. We see the system bounded by the dashed line in Figure 5.10. Notice that the force pair is *internal* to the orange–apple system. Then these forces *do* cancel each other. They play no role in accelerating the system. A force external to the system is needed for acceleration. That's where friction with the floor plays a role (Figure 5.11). When

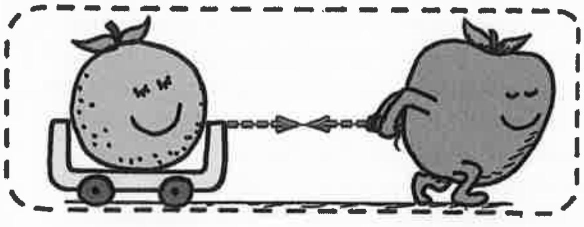


FIGURE 5.10

INTERACTIVE FIGURE

In the larger system of orange + apple, action and reaction forces are internal and cancel. If these are the only horizontal forces, with no external force, no acceleration of the system occurs.

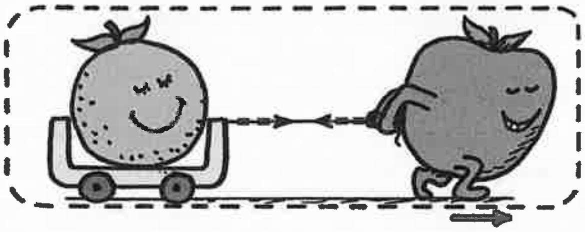


FIGURE 5.11

INTERACTIVE FIGURE

An external horizontal force occurs when the floor pushes on the apple (reaction to the apple's push on the floor). The orange–apple system accelerates.

the apple pushes against the floor, the floor simultaneously pushes on the apple—an external force on the system. The system accelerates to the right.

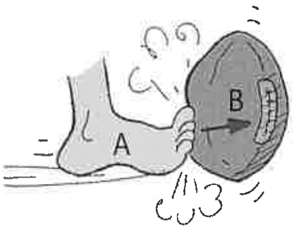


FIGURE 5.12
A acts on B, and B accelerates.

Inside a football are trillions and trillions of interatomic forces at play. They hold the ball together, but they play no role in accelerating the ball. Although every one of the interatomic forces is part of an action–reaction pair within the ball, they combine to zero, no matter how many of them there are. A force external to the football, like a kick, is needed to accelerate it. In Figure 5.12, we note a single interaction between the foot and the football.

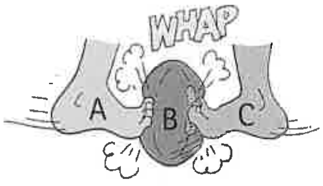


FIGURE 5.13
Both A and C act on B. They can cancel each other, so B does not accelerate.

The football in Figure 5.13, however, does not accelerate. In this case, there are two interactions occurring—two forces acting on the football. If they are simultaneous, equal, and opposite, then the net force is zero. Do the two opposing kicks make up an action–reaction pair? No, for they act on the same object, not on different objects. They may be equal and opposite, but, unless they act on different objects, they are not an action–reaction pair. Get it?

If this is confusing, it may be well to note that Newton had difficulties with the third law himself. (See insightful examples of Newton's third law on pages 21 and 22 in the *Concept Development Practice Book.*)

CHECK POINT

1. On a cold, rainy day, you find yourself in a car with a dead battery. You must push the car to move it and get it started. Why can't you move the car by remaining comfortably inside and pushing against the dashboard?
2. Why does a book sitting on a table never accelerate "spontaneously" in response to the trillions of interatomic forces acting within it?
3. We know that Earth pulls on the Moon. Does it follow that the Moon also pulls on Earth?
4. Can you identify the action and reaction forces in the case of an object falling in a vacuum?

Check Your Answers

1. In this case, the system to be accelerated is the car. If you remain inside and push on the dashboard, the force pair you produce acts and reacts within the system. These forces cancel out as far as any motion of the car is concerned. To accelerate the car, there must be an interaction between the car and something external—for example, you on the outside pushing against the road and on the car.
2. Every one of these interatomic forces is part of an action–reaction pair within the book. These forces add up to zero, no matter how many of them there are. This is what makes Newton's *first* law apply to the book. The book has zero acceleration unless an *external* force acts on it.
3. Yes, both pulls make up an action–reaction pair of forces associated with the gravitational interaction between Earth and Moon. We can say that (1) Earth pulls on Moon and (2) Moon likewise pulls on Earth; but it is more insightful to think of this as a single interaction—both Earth and Moon simultaneously pulling on each other, each with the *same* amount of force. You can't push or pull on something unless that something simultaneously pushes or pulls on you. That's the law!
4. To identify a pair of action–reaction forces in any situation, first identify the pair of interacting objects involved—Body A and Body B. Body A, the falling object, is interacting (gravitationally) with Body B, the whole Earth. So Earth pulls downward on the object (call it action), while the object pulls upward on Earth (reaction).

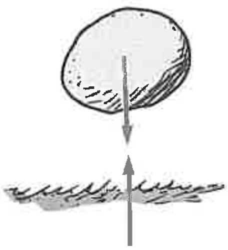


FIGURE 5.14
Earth is pulled up by the boulder with just as much force as the boulder is pulled downward by Earth.

ACTION AND REACTION ON DIFFERENT MASSES

As strange as it may first seem, a falling object pulls upward on Earth with as much force as Earth pulls downward on it. The resulting acceleration of the falling object is evident, while the upward acceleration of Earth is too small to detect. So strictly speaking, when you step off a curb, the street rises ever so slightly to meet you.

We can see that Earth accelerates slightly in response to a falling object by considering the exaggerated examples of two planetary bodies, parts (a) through (e) in Figure 5.15. The forces between bodies A and B are equal in magnitude and oppositely directed in *each* case. If acceleration of planet A is unnoticeable in (a), then it is more noticeable in (b), where the difference between the masses is less extreme. In (c), where both bodies have equal mass, acceleration of object A is as evident as it is for B. Continuing, we see that the acceleration of A becomes even more evident in (d) and even more so in (e).

The role of different masses is evident in a fired cannon. When a cannon is fired, there is an interaction between the cannon and the cannonball (Figure 5.16). A pair of forces acts on both cannon and cannonball. The force exerted on the cannonball is as great as the reaction force exerted on the cannon; hence, the cannon recoils. Since the forces are equal in magnitude, why doesn't the cannon recoil with the same speed as the cannonball? In analyzing changes in motion, Newton's second law reminds us that we must also consider the masses involved. Suppose we let F represent both the action and reaction force, m the mass of the cannonball, and ${\Large m}$ the mass of the much more massive cannon. The accelerations of the cannonball and the cannon are then found by comparing the ratio of force to mass. The accelerations are:

$$\text{Cannonball: } \frac{F}{m} = {\Large a}$$

$$\text{Cannon: } \frac{F}{\Large m} = a$$

This shows why the change in velocity of the cannonball is so large compared with the change in velocity of the cannon. A given force exerted on a small mass produces a large acceleration, while the same force exerted on a large mass produces a small acceleration.

Going back to the example of the falling object, if we used similarly exaggerated symbols to represent the acceleration of Earth reacting to a falling object, the symbol m for the Earth's mass would be astronomical in size. The force F, the weight of the falling object, divided by this large mass would result in a microscopic a to represent the acceleration of Earth toward the falling object.

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Videos

Action and Reaction on Different Masses
Action and Reaction on Rifle and Bullet

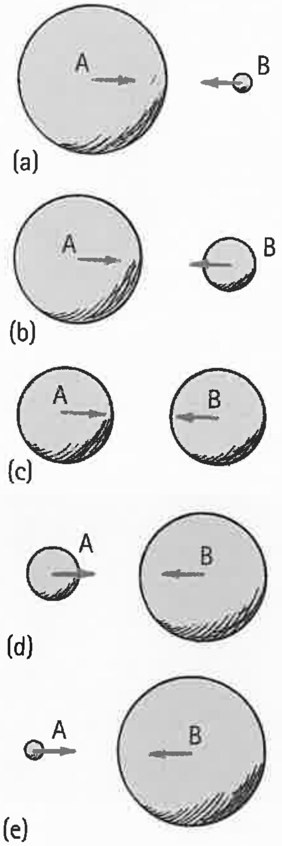


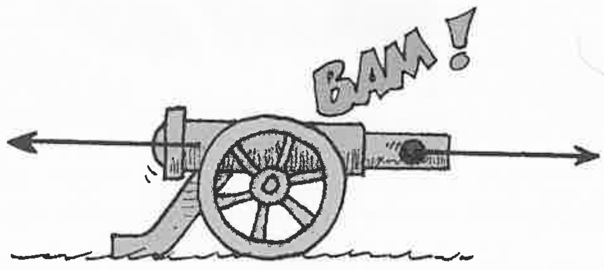
FIGURE 5.15

Which falls toward the other, A or B? Although the forces between each pair are the same, do accelerations differ?

FIGURE 5.16

INTERACTIVE FIGURE

The force exerted against the recoiling cannon is just as great as the force that drives the cannonball inside the barrel. Why, then, does the cannonball accelerate more than the cannon?



We can extend the idea of a cannon recoiling from the ball it fires to understanding rocket propulsion. Consider an inflated balloon recoiling when air is expelled (Figure 5.17). If the air is expelled downward, the balloon accelerates upward. The same principle applies to a rocket, which continually "recoils" from the ejected exhaust gas. Each molecule of exhaust gas is like a tiny cannonball shot from the rocket (Figure 5.18).

A common misconception is that a rocket is propelled by the impact of exhaust gases against the atmosphere. In fact, before the advent of rockets, it was generally thought that sending a rocket to the Moon was impossible. Why? Because there is no air above Earth's atmosphere for the rocket to push against. But this is like saying

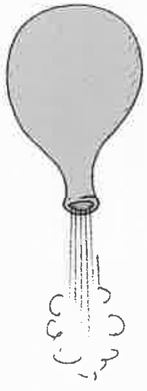


FIGURE 5.17

The balloon recoils from the escaping air, and it moves upward.

a cannon wouldn't recoil unless the cannonball had air to push against. Not true! Both the rocket and recoiling cannon accelerate because of the reaction forces exerted by the material they fire—not because of any pushes on the air. In fact, a rocket operates better above the atmosphere where there is no air resistance.

Using Newton's third law, we can understand how a helicopter gets its lifting force. The whirling blades are shaped to force air particles down (action), and the air forces the blades up (reaction). This upward reaction force is called *lift.* When lift equals the weight of the aircraft, the helicopter hovers in midair. When lift is greater, the helicopter climbs upward.

This is true for birds and airplanes. Birds fly by pushing air downward. The air in turn pushes the bird upward. When the bird is soaring, the wings must be shaped so that moving air particles are deflected downward. Slightly tilted wings that deflect oncoming air downward produce lift on an airplane. Air that is pushed downward continuously maintains lift. This supply of air is obtained by the forward motion of the aircraft, which results from propellers or jets that push air backward. The air, in turn, pushes the propellers or jets forward. We will learn in Chapter 14 that the curved surface of a wing is an airfoil, which enhances the lifting force.

We see Newton's third law at work everywhere. A fish pushes the water backward with its fins, and the water pushes the fish forward. When the wind pushes against the branches of a tree and the branches push back on the wind, we have whistling sounds. Forces are interactions between different things. Every contact requires at least a twoness; there is no way that an object can exert a force on nothing. Forces, whether large shoves or slight nudges, always occur in pairs, each of which is opposite to the other. Thus, we cannot touch without being touched.

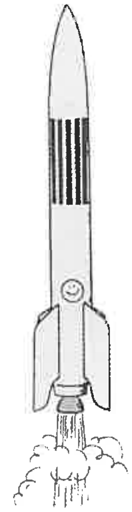


FIGURE 5.18

The rocket recoils from the "molecular cannonballs" it fires, and it moves upward.

FIGURE 5.19

Geese fly in a V formation because air pushed downward at the tips of their wings swirls upward, creating an updraft that is strongest off to the side of the bird. A trailing bird gets added lift by positioning itself in this updraft, pushes air downward, and creates another updraft for the next bird, and so on. The result is a flock flying in a V formation.

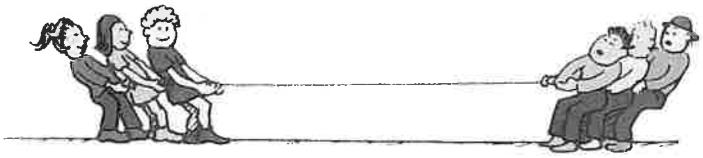
FIGURE 5.20

You cannot touch without being touched—Newton's third law.

Practicing Physics

Tug of War

Perform a tug-of-war between guys and gals. Do it on a polished floor that's somewhat slippery, with guys wearing socks and gals wearing rubber-soled shoes. Who will surely win, and why? (*Hint:* Who wins a tug-of-war, those who pull harder on the rope or those who push harder against the floor?)



CHECK POINT

1. A car accelerates along a road. Identify the force that moves the car.
2. A high-speed bus and an innocent bug have a head-on collision. The force of impact splatters the poor bug over the windshield. Is the corresponding force that the bug exerts against the windshield greater, less, or the same? Is the resulting deceleration of the bus greater than, less than, or the same as that of the bug?

Check Your Answers

1. It is the road that pushes the car along. Really! Only the road provides the horizontal force to move the car forward. How does it do this? The rotating tires of the car push back on the road (action). The road simultaneously pushes forward on the tires (reaction). How about that!
2. The magnitudes of both forces are the same, for they constitute an action–reaction force pair that makes up the interaction between the bus and the bug. The accelerations, however, are very different because the masses are different. The bug undergoes an enormous and lethal deceleration, while the bus undergoes a very tiny deceleration—so tiny that the very slight slowing of the bus is unnoticed by its passengers. But if the bug were more massive—as massive as another bus, for example—the slowing down would unfortunately be very apparent. (Can you see the wonder of physics here? Although so much is *different* for the bug and the bus, the amount of force each encounters is the *same*. Amazing!)

Jellyfish have been using rocket or jet propulsion for eons.

Summary of Newton's Three Laws

Newton's first law, the law of inertia: An object at rest tends to remain at rest; an object in motion tends to remain in motion at constant speed along a straight-line path. This property of objects to resist change in motion is called *inertia.* Mass is a measure of inertia. Objects will undergo changes in motion only in the presence of a net force.

Newton's second law, the law of acceleration: When a net force acts on an object, the object will accelerate. The acceleration is directly proportional to the net force and inversely proportional to the mass. Symbolically, $a = F/m$. Acceleration is always in the direction of the net force. When objects fall in a vacuum, the net force is simply the weight—the pull of gravity—and the acceleration is g (the symbol g denotes that acceleration is due to gravity alone). When objects fall in air, the net force is equal to the weight minus the force of air resistance, and the acceleration is less than g. If and when the force of air resistance equals the weight of a falling object, acceleration terminates, and the object falls at constant speed (called *terminal speed*).

Newton's third law, the law of action–reaction: Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first. Forces occur in pairs, one action and the other reaction, which together constitute the interaction between one object and the other. Action and reaction always occur simultaneously and act on different objects. Neither force exists without the other.

Isaac Newton's three laws of motion are rules of nature that enable us to see how beautifully so many things connect with one another. We see these rules in operation in our everyday environment.

FIGURE 5.21
This vector, scaled so that 1 cm equals 20 N, represents a force of 60 N to the right.

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Tutorial
Vectors

The valentine vector says, "I was only a scalar until you came along and gave me direction."

Vectors

We have learned that any quantity that requires both magnitude and direction for a complete description is a **vector quantity.** Examples of vector quantities include force, velocity, and acceleration. By contrast, a quantity that can be described by magnitude only, not involving direction, is called a **scalar quantity.** Mass, volume, and speed are scalar quantities.

A vector quantity is nicely represented by an arrow. When the length of the arrow is scaled to represent the quantity's magnitude, and the direction of the arrow shows the direction of the quantity, we refer to the arrow as a **vector.**

Adding vectors that act along parallel directions is simple enough: If they act in the same direction, they add; if they act in opposite directions, they subtract. The sum of two or more vectors is called their **resultant.** To find the resultant of two vectors that don't act in exactly the same or opposite direction, we use the *parallelogram rule.*[2] Construct a parallelogram wherein the two vectors are adjacent sides—the diagonal of the parallelogram shows the resultant. In Figure 5.22, the parallelograms are rectangles.

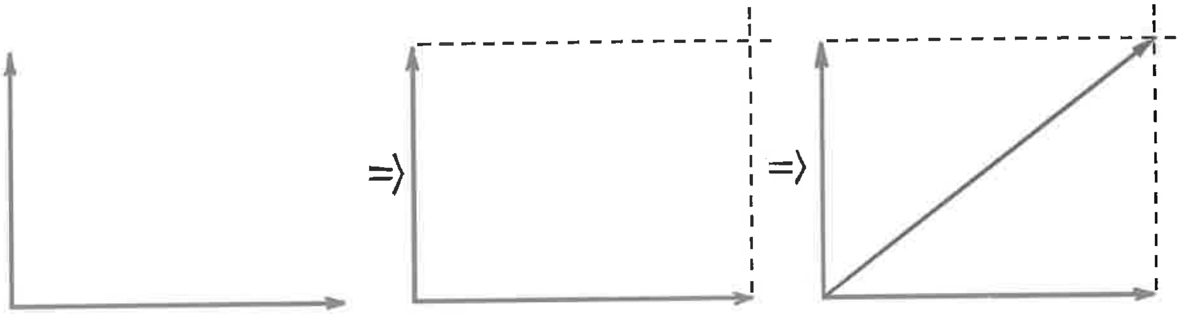

FIGURE 5.22
INTERACTIVE FIGURE
The pair of vectors at right angles to each other make two sides of a rectangle, the diagonal of which is their resultant.

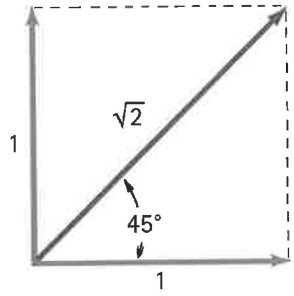

FIGURE 5.23
When a pair of equal-length vectors at right angles to each other are added, they form a square. The diagonal of the square is the resultant, $\sqrt{2}$ times the length of either side.

In the special case of two vectors that are equal in magnitude and perpendicular to each other, the parallelogram is a square (Figure 5.23). Since for any square the length of a diagonal is $\sqrt{2}$, or 1.41, times one of the sides, the resultant is $\sqrt{2}$ times one of the vectors. For example, the resultant of two equal vectors of magnitude 100 acting at a right angle to each other is 141.

FORCE VECTORS

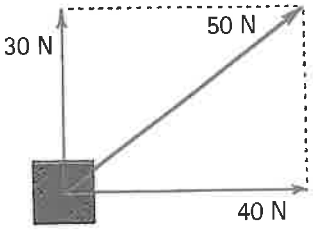

FIGURE 5.24
The resultant of the 30-N and 40-N forces is 50 N.

Figure 5.24 shows a pair of forces acting on a box. One is 30 newtons and the other is 40 newtons. Simple measurement shows the resultant of this pair of forces is 50 newtons.

Figure 5.25 shows Nellie Newton hanging at rest from a clothesline. Note that the clothesline acts like a pair of ropes that make different angles with the vertical. Which side has the greater tension? Investigation will show there are three forces acting on Nellie: her weight, a tension in the left-hand side of the rope, and a tension in the right-hand side of the rope. Because of the different angles, different rope tensions will occur in each side. Figure 5.25 shows a step-by-step solution. Because Nellie hangs in equilibrium, her weight must be supported by two rope

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[2] A parallelogram is a four-sided figure with opposite sides parallel to each other. Usually, you determine the length of the diagonal by measurement; but, in the special case in which the two vectors **X** and **Y** are perpendicular (a square or a rectangle), you can apply the Pythagorean Theorem, $\mathbf{R}^2 = \mathbf{X}^2 + \mathbf{Y}^2$, to find the resultant: $\mathbf{R} = \sqrt{\mathbf{X}^2 + \mathbf{Y}^2}$.

tensions, which must add vectorially to be equal and opposite to her weight. The parallelogram rule shows that the tension in the right-hand rope is greater than the tension in the left-hand rope. If you measure the vectors, you'll see that tension in the right rope is about twice the tension in the left rope. Both rope tensions combine to support her weight.

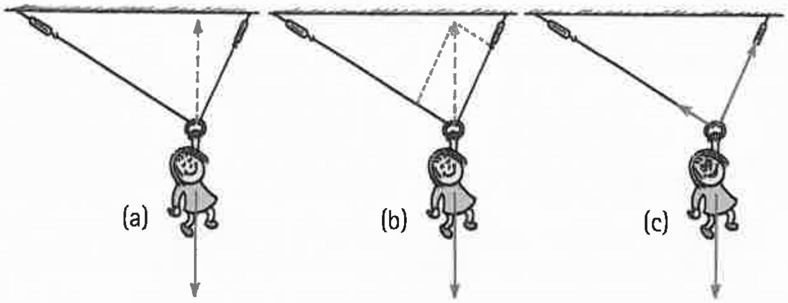

FIGURE 5.25

INTERACTIVE FIGURE

(a) Nellie's weight is shown by the downward vertical vector. An equal and opposite vector is needed for equilibrium, shown by the dashed vector. (b) This dashed vector is the diagonal of a parallelogram defined by the green lines. (c) Both rope tensions are shown by the constructed vectors. Tension is greater in the right rope, the one more likely to break.

More about force vectors can be found in Appendix D at the end of this book and in the *Practicing Physics* book.

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Vector Representations: How to Add and Subtract Vectors

Geometric Addition of Vectors

VELOCITY VECTORS

Recall, from Chapter 3, the difference between speed and velocity—speed is a measure of "how fast"; velocity is a measure of both how fast and "in which direction." If the speedometer in a car reads 100 kilometers per hour (km/h), you know your speed. If there is also a compass on the dashboard, indicating that the car is moving due north, for example, you know your velocity—100 km/h north. To know your velocity is to know your speed and your direction.

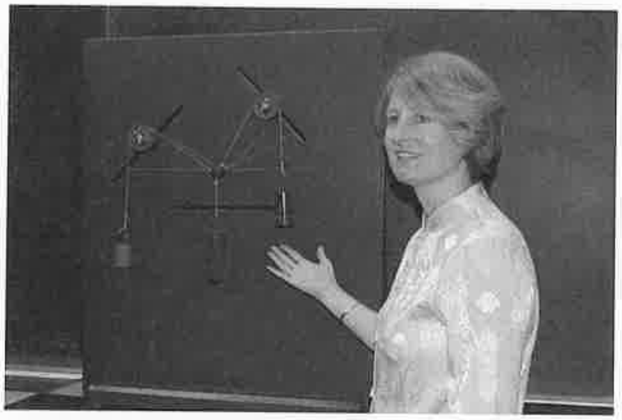


FIGURE 5.26

Diana Lininger Markham illustrates the vector arrangement of Figure 5.25.

Consider an airplane flying due north at 80 km/h relative to the surrounding air. Suppose that the plane is caught in a 60-km/h crosswind (wind blowing at right angles to the direction of the airplane) that blows it off its intended course. This example is represented with vectors in Figure 5.27 with velocity vectors scaled so that 1 centimeter (cm) represents 20 km/h. Thus, the 80-km/h velocity of the airplane is shown by the 4-cm vector, and the 60-km/h crosswind is shown by the 3-cm vector. The diagonal of the constructed parallelogram (a rectangle, in this case) measures 5 cm, which represents 100 km/h. So the airplane moves at 100 km/h relative to the ground, in a direction between north and northeast.

The pair of 6-unit and 8-unit vectors at right angles to each other say, "We may be a six and an eight, but together we're a perfect ten."

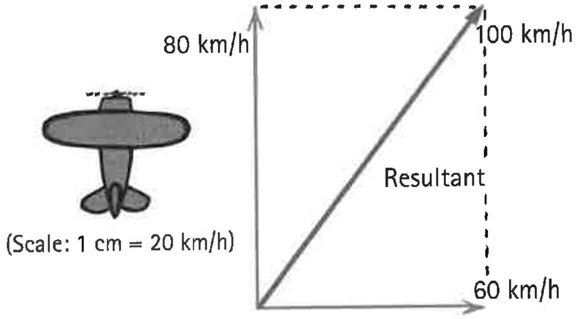


FIGURE 5.27
The 60-km/h crosswind blows the 80-km/h aircraft off course at 100 km/h.

CHECK POINT

Consider a motorboat that normally travels 10 km/h in still water. If the boat heads directly across the river, which also flows at a rate of 10 km/h, what will be its velocity relative to the shore?

Check Your Answer

When the boat heads cross-stream (at right angles to the river flow), its velocity is 14.1 km/h, 45 degrees downstream (in accord with the diagram in Figure 5.23).

COMPONENTS OF VECTORS

Just as two vectors at right angles can be combined into one resultant vector, any vector can be resolved into two *component* vectors perpendicular to each other. These two vectors are known as the **components** of the given vector they replace (Figure 5.28). The process of determining the components of a vector is called *resolution.* Any vector drawn on a piece of paper can be resolved into a vertical and a horizontal component.

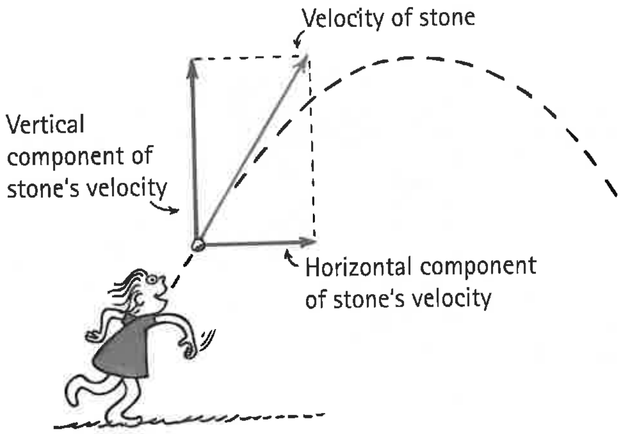


FIGURE 5.28
The horizontal and vertical components of a stone's velocity.

Vector resolution is illustrated in Figure 5.29. A vector **V** is drawn in the proper direction to represent a vector quantity. Then vertical and horizontal lines *(axes)* are

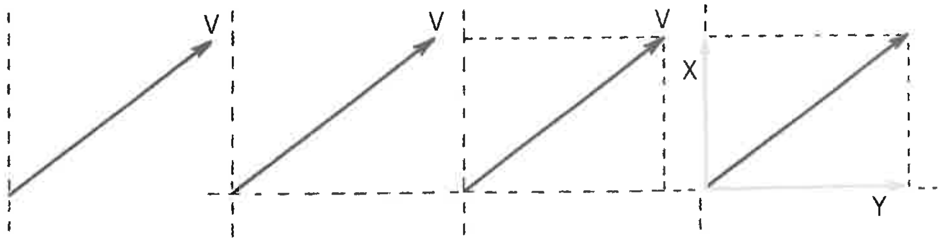


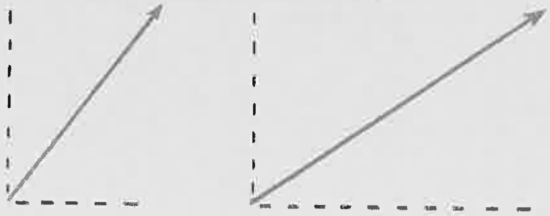
FIGURE 5.29
Construction of the vertical and horizontal components of a vector.

drawn at the tail of the vector. Next, a rectangle is drawn that has **V** as its diagonal. The sides of this rectangle are the desired components, vectors **X** and **Y.** In reverse, note that the vector sum of vectors **X** and **Y** is **V.**

We'll return to vector components when we treat projectile motion in Chapter 10.

CHECK POINT

With a ruler, draw the horizontal and vertical components of the two vectors shown. Measure the components and compare your findings with the answers given at the bottom of the page.



Answers

Left vector: The horizontal component is 2 cm; the vertical component is 2.6 cm.
Right vector: The horizontal component is 3.8 cm; the vertical component is 2.6 cm.

SUMMARY OF TERMS

Newton's third law Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first.

Vector quantity A quantity that has both magnitude and direction. Examples are force, velocity, and acceleration.

Scalar quantity A quantity that has magnitude but not direction. Examples are mass, volume, and speed.

Vector An arrow drawn to scale used to represent a vector quantity.

Resultant The net result of a combination of two or more vectors.

Components Mutually perpendicular vectors, usually horizontal and vertical, whose vector sum is a given vector.

REVIEW QUESTIONS

Forces and Interactions

1. When you push against a wall with your fingers, they bend because they experience a force. Identify this force.
2. A boxer can hit a heavy bag with great force. Why can't he hit a piece of tissue paper in midair with the same amount of force?
3. How many forces are required for an interaction?

Newton's Third Law of Motion

4. State Newton's third law of motion.
5. Consider hitting a baseball with a bat. If we call the force on the bat against the ball the *action* force, identify the *reaction* force.
6. Consider the apple and the orange (Figure 5.9). If the system is considered to be only the orange, is there a net force on the system when the apple pulls?
7. If the system is considered to be the apple and the orange together (Figure 5.10), is there a net force on the system when the apple pulls (ignoring friction with the floor)?
8. To produce a net force on a system, must there be an externally applied net force?
9. Consider the system of a single football. If you kick it, is there a net force to accelerate the system? If a friend kicks it at the same time with an equal and opposite force, is there a net force to accelerate the system?

Action and Reaction on Different Masses

10. Earth pulls down on you with a gravitational force that you call your weight. Do you pull up on Earth with the same amount of force?
11. If the forces that act on a cannonball and the recoiling cannon from which it is fired are equal in magnitude,

why do the cannonball and cannon have very different accelerations?

12. Identify the force that propels a rocket.
13. How does a helicopter get its lifting force?
14. Can you physically touch a person without that person touching you with the same amount of force?

Summary of Newton's Three Laws

15. Fill in the blanks: Newton's first law is often called the law of ________; Newton's second law is the law of ________; and Newton's third law is the law of ________ and ________.
16. Which of the three laws deals with interactions?

Vectors

17. Cite three examples of a vector quantity and three examples of a scalar quantity.
18. Why is speed considered a scalar and velocity a vector?
19. According to the parallelogram rule, what quantity is represented by the diagonal of a constructed parallelogram?
20. Consider Nellie hanging at rest in Figure 5.25. If the ropes were vertical, with no angle involved, what would be the tension in each rope?
21. When Nellie's ropes make an angle, what quantity must be equal and opposite to her weight?
22. When a pair of vectors are at right angles, is the resultant always greater in magnitude than either of the vectors separately?

PROJECT

Hold your hand like a flat wing outside the window of a moving automobile. Then slightly tilt the front edge upward and notice the lifting effect. Can you see Newton's laws at work here?

PLUG AND CHUG

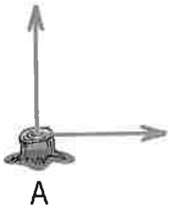
1. Calculate the resultant of the pair of velocities 100 km/h north and 75 km/h south. Calculate the resultant if both of the velocities are directed north.

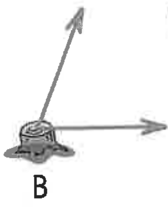
Resultant of two vectors at right angles to each other:
$\mathbf{R} = \sqrt{X^2 + Y^2}$

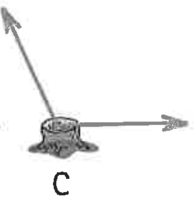
2. Calculate the magnitude of the resultant of a pair of 100-km/h velocity vectors that are at right angles to each other.
3. Calculate the resultant of a horizontal vector with a magnitude of 4 units and a vertical vector with a magnitude of 3 units.
4. Calculate the resultant velocity of an airplane that normally flies at 200 km/h if it encounters a 50-km/h wind from the side (at a right angle to the airplane).

RANKING

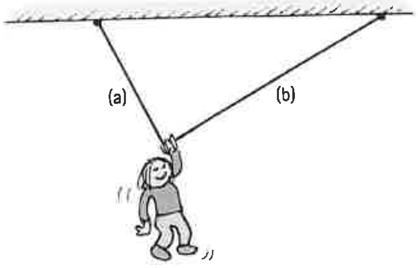
1. As seen from above, a stubborn stump is pulled by a pair of ropes, each with a force of 200 N, but at different angles as shown. From greatest to least, rank the net force on the stump.





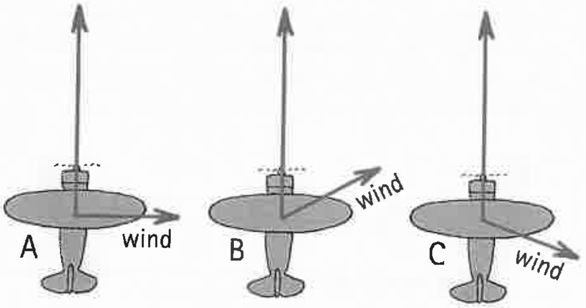


2. Nellie Newton hangs motionless by one hand from a clothesline. Which side of the line, a or b, has the greater

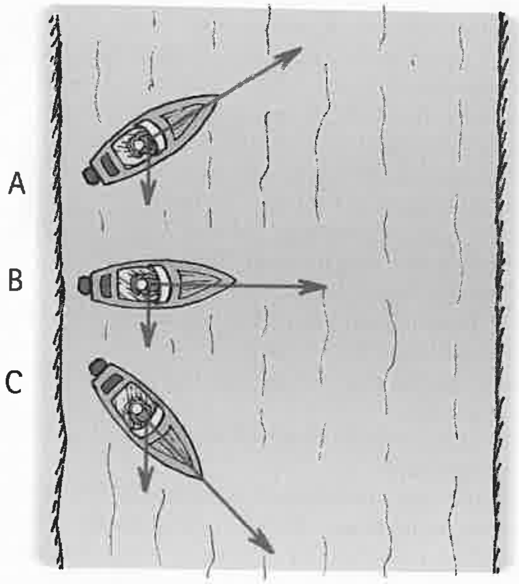


a. horizontal component of tension?
b. vertical component of tension?
c. tension?

3. Here we see a top view of an airplane being blown off course by wind in three different directions. Use a pencil and the parallelogram rule and sketch the vectors that show the resulting velocities for each case. Rank the speeds of the airplane across the ground from fastest to slowest.



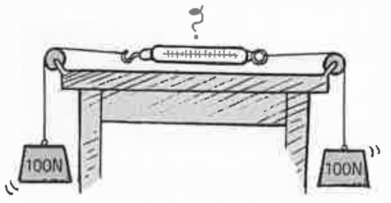
4. Here we see top views of three motorboats crossing a river. All have the same speed relative to the water, and all experience the same river flow. Construct resultant vectors showing the speed and direction of the boats. Rank them from most to least for
a. the time for the boats to reach the opposite shore.
b. the fastest ride.



EXERCISES

1. A rocket becomes progressively easier to accelerate as it travels through space. Why is this so? (*Hint:* About 90% of the mass of a newly launched rocket is fuel.)
2. The photo shows Steve Hewitt and daughter Gretchen. Is Gretchen touching her dad, or is dad touching her? Explain.

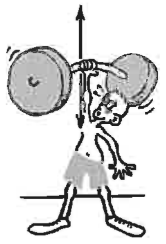
3. When you rub your hands together, can you push harder on one hand than the other?
4. For each of the following interactions, identify action and reaction forces. (a) A hammer hits a nail. (b) Earth gravity pulls down on a book. (c) A helicopter blade pushes air downward.
5. You hold an apple over your head. (a) Identify all the forces acting on the apple and their reaction forces. (b) When you drop the apple, identify all the forces acting on it as it falls and the corresponding reaction forces. Neglect air drag.
6. Identify the action–reaction pairs of forces for the following situations: (a) You step off a curb. (b) You pat your tutor on the back. (c) A wave hits a rocky shore.
7. Consider a baseball player batting a ball. (a) Identify the action–reaction pairs when the ball is being hit and (b) while the ball is in flight.
8. What physics is involved for a passenger feeling pushed backward into the seat of an airplane when it accelerates along the runway during takeoff?
9. If you drop a rubber ball on the floor, it bounces back up. What force acts on the ball to provide the bounce?
10. When you kick a football, what action and reaction forces are involved? Which force, if any, is greater?
11. Is it true that when you drop from a branch to the ground below, you pull upward on Earth? If so, then why is the acceleration of Earth not noticed?
12. Within a book on a table, there are billions of forces pushing and pulling on all the molecules. Why is it that these forces never by chance add up to a net force in one direction, causing the book to accelerate "spontaneously" across the table?
13. Two 100-N weights are attached to a spring scale as shown. Does the scale read 0, 100, or 200 N, or does it give some other reading? (*Hint:* Would it read any differently if one of the ropes were tied to the wall instead of to the hanging 100-N weight?)



14. If you exert a horizontal force of 200 N to slide a crate across a factory floor at constant velocity, how much friction is exerted by the floor on the crate? Is the force of friction equal and oppositely directed to your 200-N

push? If the force of friction isn't the reaction force to your push, what is?

15. When the athlete holds the barbell overhead, the reaction force is the weight of the barbell on his hand. How does this force vary for the case in which the barbell is accelerated upward? Downward?



16. Consider the two forces acting on the person who stands still—namely, the downward pull of gravity and the upward support of the floor. Are these forces equal and opposite? Do they form an action–reaction pair? Why or why not?

17. Why can you exert greater force on the pedals of a bicycle if you pull up on the handlebars?

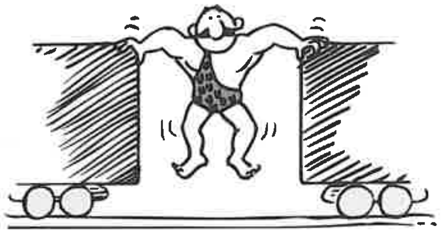
18. Does a baseball bat slow down when it hits a ball? Defend your answer.

19. Why does a rope climber pull downward on the rope to move upward?

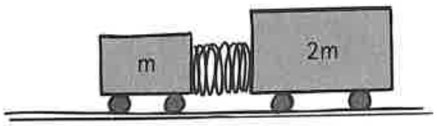
20. A farmer urges his horse to pull a wagon. The horse refuses, saying that to try would be futile, for it would flout Newton's third law. The horse concludes that she can't exert a greater force on the wagon than the wagon exerts on her and, therefore, that she won't be able to accelerate the wagon. What is your explanation to convince the horse to pull?

21. You push a heavy car by hand. The car, in turn, pushes back with an opposite but equal force on you. Doesn't this mean that the forces cancel one another, making acceleration impossible? Why or why not?

22. The strong man will push the two initially stationary freight cars of equal mass apart before he himself drops straight to the ground. Is it possible for him to give either of the cars a greater speed than the other? Why or why not?



23. Suppose that two carts, one twice as massive as the other, fly apart when the compressed spring that joins them is released. What is the acceleration of the heavier cart relative to that of the lighter cart as they start to move apart?



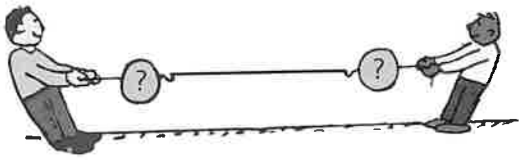
24. If a Mack truck and Honda Civic have a head-on collision, upon which vehicle is the impact force greater? Which vehicle experiences the greater deceleration? Explain your answers.

25. Ken and Joanne are astronauts floating some distance apart in space. They are joined by a safety cord whose ends are tied around their waists. If Ken starts pulling on the cord, will he pull Joanne toward him, or will he pull himself toward Joanne, or will both astronauts move? Explain.

26. Which team wins in a tug-of-war—the team that pulls harder on the rope, or the team that pushes harder against the ground? Explain.

27. In a tug-of-war between Sam and Maddy, each pulls on the rope with a force of 250 N. What is the tension in the rope? If both remain motionless, what horizontal force does each exert against the ground?

28. Your instructor challenges you and your friend to each pull on a pair of scales attached to the ends of a horizontal rope, in tug-of-war fashion, so that the readings on the scales will differ. Can this be done? Explain.



29. Two people of equal mass attempt a tug-of-war with a 12-m rope while standing on frictionless ice. When they pull on the rope, each of them slides toward the other. How do their accelerations compare, and how far does each person slide before they meet?

30. What aspect of physics was not known by the writer of this newspaper editorial that ridiculed early experiments by Robert H. Goddard on rocket propulsion above Earth's atmosphere? "Professor Goddard . . . does not know the relation of action to reaction, and of the need to have something better than a vacuum against which to react . . . he seems to lack the knowledge ladled out daily in high schools."

31. Which of the following are scalar quantities, which are vector quantities, and which are neither? (a) velocity; (b) age; (c) speed; (d) acceleration; (e) temperature.

32. What can you correctly say about two vectors that add together to equal zero?

33. Can a pair of vectors with unequal magnitudes ever add to zero? Can three unequal vectors add to zero? Defend your answers.

34. When can a nonzero vector have a zero horizontal component?

35. When, if ever, can a vector quantity be added to a scalar quantity?

36. Which is more likely to break—a hammock stretched tightly between a pair of trees or one that sags more when you sit on it?

37. A heavy bird sits on a clothesline. Will the tension in the clothesline be greater if the line sags a lot or if it sags a little?

38. The rope supports a lantern that weighs 50 N. Is the tension in the rope less than, equal to, or more than 50 N? Use the parallelogram rule to defend your answer.

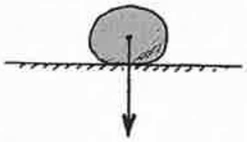
39. The rope is repositioned as shown and still supports the 50-N lantern. Is the tension in the rope less than, equal to, or more than 50 N? Use the parallelogram rule to defend your answer.

40. Why does vertically falling rain make slanted streaks on the side windows of a moving automobile? If the streaks make an angle of 45°, what does this tell you about the relative speed of the car and the falling rain?

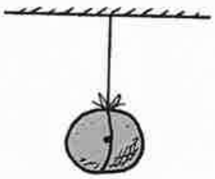
41. A balloon floats motionless in the air. A balloonist begins climbing the supporting cable. In which direction does the balloon move as the balloonist climbs? Defend your answer.

42. Consider a stone at rest on the ground. There are two interactions that involve the stone. One is between the stone and Earth as a whole: Earth pulls down on the stone (its weight) and the stone pulls up on Earth. What is the other interaction?

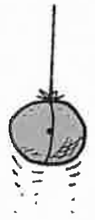
43. A stone is shown at rest on the ground. (a) The vector shows the weight of the stone. Complete the vector diagram showing another vector that results in zero net force on the stone. (b) What is the conventional name of the vector you have drawn?



44. Here a stone is suspended at rest by a string. (a) Draw force vectors for all the forces that act on the stone. (b) Should your vectors have a zero resultant? (c) Why or why not?



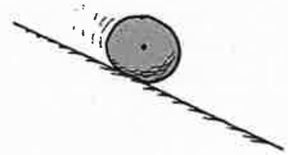
45. Here the same stone is being accelerated vertically upward. (a) Draw force vectors to some suitable scale showing relative forces acting on the stone. (b) Which is the longer vector, and why?



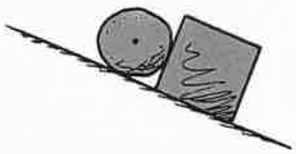
46. Suppose the string in the preceding exercise breaks and the stone slows in its upward motion. Draw a force vector diagram of the stone when it reaches the top of its path.

47. What is the acceleration of the stone of Exercise 46 at the top of its path?

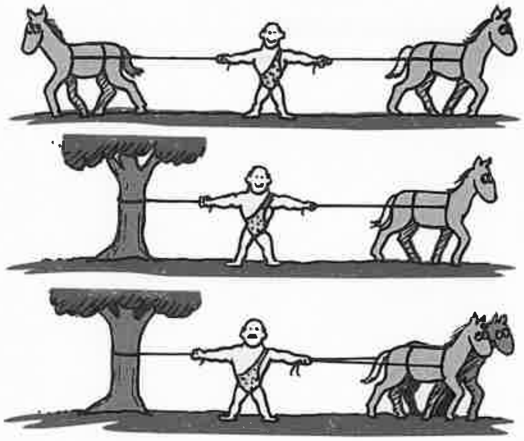
48. Here the stone is sliding down a friction-free incline. (a) Identify the forces that act on it, and draw appropriate force vectors. (b) By the parallelogram rule, construct the resultant force on the stone (carefully showing that it has a direction parallel to the incline—the same direction as the stone's acceleration).



49. Here the stone is at rest, interacting with both the surface of the incline and the block. (a) Identify all the forces that act on the stone, and draw appropriate force vectors. (b) Show that the net force on the stone is zero. (*Hint 1:* There are two normal forces on the stone. *Hint 2:* Be sure the vectors you draw are for forces that act *on* the stone, not *by* the stone on the surfaces.)



50. The strong man can withstand the tension force exerted by the two horses pulling in opposite directions. How would the tension compare if only one horse pulled and the left rope were tied to a tree? How would the tension compare if the two horses pulled in the same direction, with the left rope tied to the tree?



PROBLEMS

1. A boxer punches a sheet of paper in midair and brings it from rest up to a speed of 25 m/s in 0.05 s. (a) What acceleration is imparted to the paper? (b) If the mass of the paper is 0.003 kg, what force does the boxer exert on it? (c) How much force does the paper exert on the boxer?

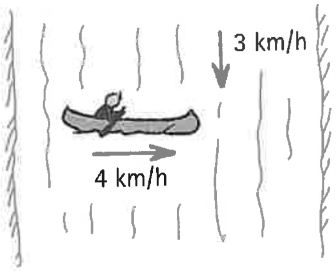
2. If you stand next to a wall on a frictionless skateboard and push the wall with a force of 40 N, how hard does the wall push on you? If your mass is 80 kg, show that your acceleration is 0.5 m/s^2.

3. If raindrops fall vertically at a speed of 3 m/s and you are running at 4 m/s, how fast do they hit your face?

4. Forces of 3.0 N and 4.0 N act at right angles on a block of mass 2.0 kg. Show that the acceleration of the block is 2.5 m/s^2.

5. Consider an airplane that normally has an airspeed of 100 km/h in a 100-km/h crosswind blowing from west to east. Calculate its ground velocity when its nose is pointed north in the crosswind.

6. You are paddling a canoe at a speed of 4 km/h directly across a river that flows at 3 km/h, as shown in the figure. (a) What is your resultant speed relative to the shore? (b) In approximately what direction should you paddle the canoe so that it reaches a destination directly across the river?



• 7. When two identical air pucks with repelling magnets are held together on an air table and released, they end up moving in opposite directions at the same speed, *v*. Assume the mass of one of the pucks is doubled and the procedure is repeated.

   a. From Newton's third law, derive an equation that shows how the final speed of the double-mass puck compares with the speed of the single puck.
   b. Calculate the speed of the double-mass puck if the single puck moves away at 0.4 m/s.

CHAPTER 5 ONLINE RESOURCES

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Interactive Figures

- 5.1, 5.8, 5.9, 5.10, 5.11, 5.16, 5.22, 5.25

Tutorials

- Newton's Third Law
- Vectors

Videos

- Forces and Interaction
- Action and Reaction on Different Masses
- Action and Reaction on Rifle and Bullet
- Vector Representation: How to Add and Subtract Vectors
- Geometrical Addition of Vectors

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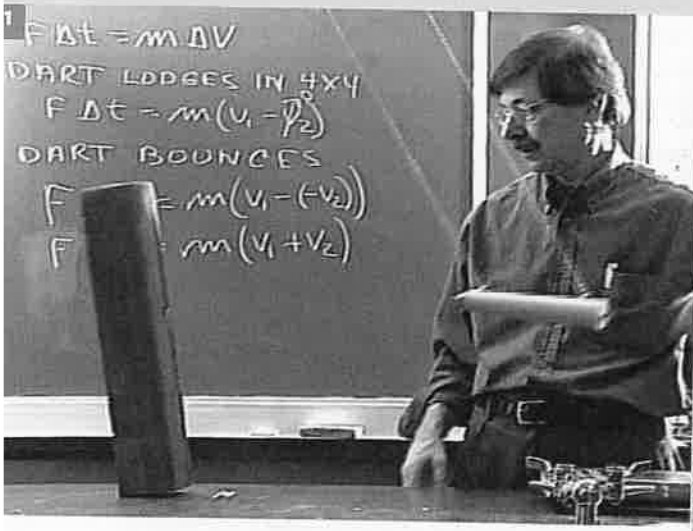
6 Momentum



1 Howie Brand demonstrates the different results when a dart bounces from a wooden block, rather than sticking to it. A bouncing dart produces more impulse, which tips the block. 2 Likewise for the Pelton wheel, where water bouncing from the curved paddles produces more impulse, which imparts more momentum to the wheel. 3 Momentum is mass times speed, as Alex Hewitt shows with his skateboard.

The gold rush that started in 1849 in California brought wealth to many who arrived with picks, shovels, and equipment for gold mining. But mining wasn't the only way to make money in the gold rush. Lester A. Pelton showed up without pick, shovel, or mining equipment and made his fortune by applying some physics (common sense) to the waterwheels used in mining operations at the time. He saw that the low efficiency of waterwheels was due to their flat paddles. Pelton designed a curved paddle with a ridge in the middle that caused the water to make a pair of U-turns upon impact. This produced more force on the paddles, just as more force is required to catch a ball and toss it back than to merely stop the ball. Water made to bounce exerts a greater impulse on the wheel. Pelton patented his idea and ushered in the impulse water turbine, more simply called the Pelton wheel (above). Pelton's story illustrates the fact that physics can indeed enrich your life in more ways than one.

We begin this chapter by examining the concept of momentum and the impulse that causes it to change.

Lester A. Pelton (1829–1908)

FIGURE 6.1

The boulder, unfortunately, has more momentum than the runner.

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Tutorial

Newton's Third Law and Momentum

Video

Definition of Momentum

Momentum

We all know that a heavy truck is harder to stop than a small car moving at the same speed. We state this fact by saying that the truck has more momentum than the car. By **momentum** we mean inertia in motion. More specifically, momentum is defined as the product of the mass of an object and its velocity; that is,

$$\text{Momentum} = \text{mass} \times \text{velocity}$$

Or, in shorthand notation,

$$\text{Momentum} = mv$$

When direction is not an important factor, we can say:

$$\text{Momentum} = \text{mass} \times \text{speed}$$

which we still abbreviate *mv*.

We can see from the definition that a moving object can have a large momentum if either its mass or its velocity is large or if both its mass and its velocity are large. The truck has more momentum than the car moving at the same speed because it has a greater mass. We can see that a huge ship moving at a small speed can have a large momentum, as can a small bullet moving at a high speed. And, of course, a huge object moving at a high speed, such as a massive truck rolling down a steep hill with no brakes, has a huge momentum, whereas the same truck at rest has no momentum at all—because the v term in mv is zero.

FIGURE 6.2

Why are the engines of a supertanker normally cut off 25 km from port? Timing is especially important when changing momentum.

Impulse

If the momentum of an object changes, then either the mass or the velocity or both change. If the mass remains unchanged, as is most often the case, then the velocity changes and acceleration occurs. What produces acceleration? We know the answer is *force*. The greater the force acting on an object, the greater its change in velocity and, hence, the greater its change in momentum.

But something else is important in changing momentum: time—how long a time the force acts. If you apply a brief force to a stalled automobile, you produce a change in its momentum. Apply the same force over an extended period of time, and you produce a greater change in the automobile's momentum. A force sustained for a long time produces more change in momentum than does the same force applied briefly. So, both force and time interval are important in changing momentum.

The quantity *force* × *time interval* is called **impulse.** In shorthand notation

$$\text{Impulse} = Ft$$

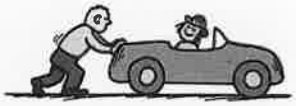

FIGURE 6.3

When you push with the same force for twice the time, you impart twice the impulse and produce twice the change in momentum.

CHECK POINT

1. Which has more momentum, a 1-ton car moving at 100 km/h or a 2-ton truck moving at 50 km/h?
2. Does a moving object have impulse?
3. Does a moving object have momentum?
4. For the same force, which cannon imparts a greater impulse to a cannonball—a long cannon or a short one?

Check Your Answers

1. Both have the same momentum (1 ton × 100 km/h = 2 ton × 50 km/h).
2. No, impulse is not something an object *has,* like momentum. Impulse is what an object can *provide* or what it can *experience* when it interacts with some other object. An object cannot possess impulse just as it cannot possess force.
3. Yes, but, like velocity, in a relative sense—that is, with respect to a frame of reference, usually Earth's surface. The momentum possessed by a moving object with respect to a stationary point on Earth may be quite different from the momentum it possesses with respect to another moving object.
4. The long cannon will impart a greater impulse because the force acts over a longer time. (A greater impulse produces a greater change in momentum, so a long cannon will impart more speed to a cannonball than a short cannon.)

Timing is important especially when you're changing your momentum.

Impulse Changes Momentum

The greater the impulse exerted on something, the greater will be the change in momentum. The exact relationship is

$$\text{Impulse} = \text{change in momentum}$$

We can express all terms in this relationship in shorthand notation and introduce the delta symbol Δ (a letter in the Greek alphabet used to denote "change in" or "difference in"):[1]

$$Ft = \Delta(mv)$$

The impulse–momentum relationship helps us to analyze many examples in which forces act and motion changes. Sometimes the impulse can be considered to be the cause of a change of momentum. Sometimes a change of momentum can be considered to be the cause of an impulse. It doesn't matter which way you think about it. The important thing is that impulse and change of momentum are always linked. Here we will consider some ordinary examples in which impulse is related to

The symbol p is often used to represent momentum.

---

[1] This relationship is derived by rearranging Newton's second law to make the time factor more evident. If we equate the formula for acceleration, $a = F/m$, with what acceleration actually is, $a = \Delta v/\Delta t$, we get $F/m = \Delta v/\Delta t$. From this we derive $F\Delta t = \Delta(mv)$ Calling Δt simply t, the time interval, $Ft = \Delta(mv)$.

FIGURE 6.4
The force of impact on a golf ball varies throughout the duration of impact.

(1) increasing momentum, (2) decreasing momentum over a long time, and (3) decreasing momentum over a short time.

CASE 1: INCREASING MOMENTUM

To increase the momentum of an object, it makes sense to apply the greatest force possible for as long as possible. A golfer teeing off and a baseball player trying for a home run do both of these things when they swing as hard as possible and follow through with their swings. Following through extends the time of contact.

The forces involved in impulses usually vary from instant to instant. For example, a golf club that strikes a ball exerts zero force on the ball until it comes in contact; then the force increases rapidly as the ball is distorted (Figure 6.4). The force then diminishes as the ball comes up to speed and returns to its original shape. So, when we speak of such forces in this chapter, we mean the *average* force.

CASE 2: DECREASING MOMENTUM

If you were in a car that was out of control and you had to choose between hitting a concrete wall or a haystack, you wouldn't have to call on your knowledge of physics to make up your mind. Common sense tells you to choose the haystack. But, knowing the physics helps you to understand *why* hitting a soft object is entirely different than hitting a hard one. In the case of hitting either the wall or the haystack and coming to a stop, it takes the *same* impulse to decrease your momentum to zero. The same impulse does not mean the same amount of force or the same amount of time; rather it means the same *product* of force and time. By hitting the haystack instead of the wall, you extend the *time during which your momentum is brought to zero.* A longer time interval reduces the force and decreases the resulting deceleration. For example, if the time interval is extended 100 times, the force is reduced to a hundredth. Whenever we wish the force to be small, we extend the time of contact. Hence, the padded dashboards and airbags in motor vehicles.

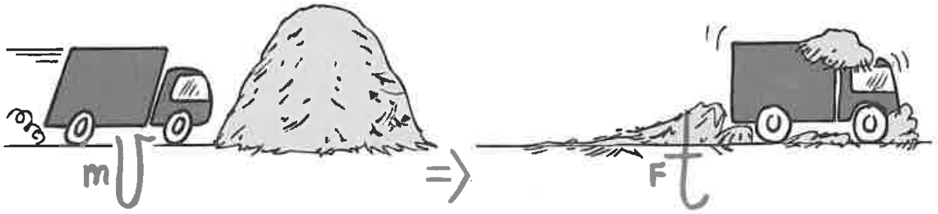

FIGURE 6.5
If the change in momentum occurs over a long time, the hitting force is small.

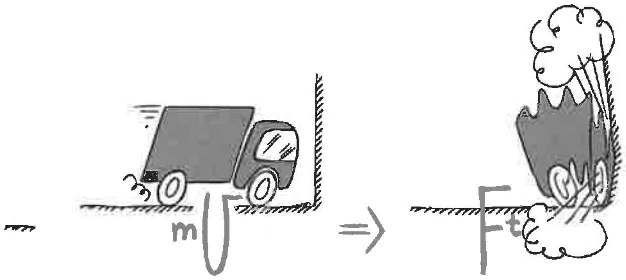

FIGURE 6.6
If the change in momentum occurs over a short time, the hitting force is large.

PhysicsPlace.com™
Video
Changing Momentum—Follow-Through

When jumping from an elevated position down to the ground, what happens if you keep your legs straight and stiff? Ouch! Instead, you bend your knees when your feet make contact with the ground. By doing so you extend the time during which your momentum decreases by 10 to 20 times that of a stiff-legged, abrupt landing. The resulting force on your bones is reduced by 10 to 20 times. A wrestler thrown to the floor tries to extend his time of impact with the mat by relaxing his muscles and spreading the impact into a series of smaller ones as his foot, knee, hip, ribs, and shoulder successively hit the mat. Of course, falling on a mat is preferable to falling on a solid floor because the mat also increases the time during which the force acts.

The safety net used by circus acrobats is a good example of how to achieve the impulse needed for a safe landing. The safety net reduces the force experienced by a fallen acrobat by substantially increasing the time interval during which the force acts. If you're about to catch a fast baseball with your bare hand, you extend your hand forward so you'll have plenty of room to let your hand move backward after you make contact with the ball. You extend the time of impact and thereby reduce the force of impact. Similarly, a boxer rides or rolls with the punch to reduce the force of impact (Figure 6.8).

FIGURE 6.7

A large change in momentum over a long time requires a safely small average force.

CASE 3: DECREASING MOMENTUM OVER A SHORT TIME

When boxing, if you move into a punch instead of away, you're in trouble. Likewise, if you catch a high-speed baseball while your hand moves toward the ball instead of away upon contact. Or, when your car is out of control, if you drive it into a concrete wall instead of a haystack, you're really in trouble. In these cases of short impact times, the impact forces are large. Remember that, for an object brought to rest, the impulse is the same, no matter how it is stopped. But, if the time is short, the force will be large.

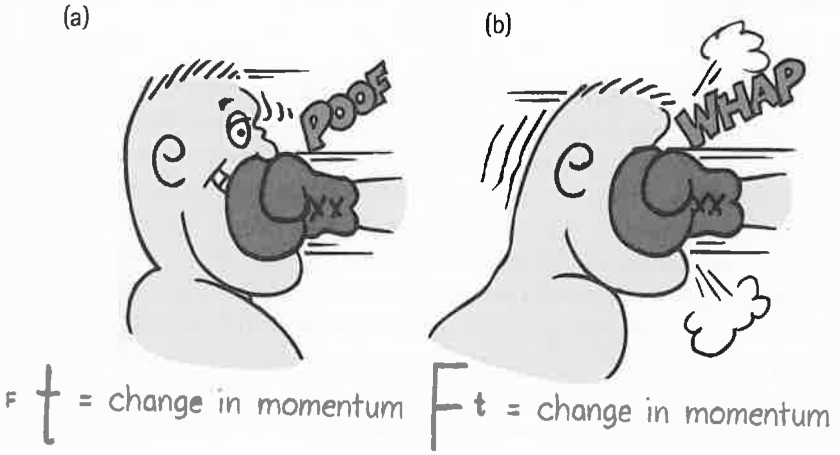

FIGURE 6.8

In both cases, the impulse provided by the boxer's jaw reduces the momentum of the punch. (a) When the boxer moves away (rides with the punch), he extends the time and diminishes the force. (b) If the boxer moves into the glove, the time is reduced and he must withstand a greater force.

PhysicsPlace.com™
Video
Decreasing Momentum Over a Short Time

The idea of short time of contact explains how a karate expert can split a stack of bricks with the blow of her bare hand (Figure 6.9). She brings her arm and hand swiftly against the bricks with considerable momentum. This momentum is quickly reduced when she delivers an impulse to the bricks. The impulse is the force of her hand against the bricks multiplied by the time during which her hand makes contact with the bricks. By swift execution, she makes the time of contact very brief and correspondingly makes the force of impact huge. If her hand is made to bounce upon impact, the force is even greater.

FIGURE 6.9

Cassy imparts a large impulse to the bricks in a short time and produces a considerable force.

Different forces exerted over different time intervals can produce the same impulse.

Ft or Ft

CHECK POINT

1. If the boxer in Figure 6.8 is able to increase the duration of impact 3 times as long by riding with the punch, by how much will the force of impact be reduced?
2. If the boxer instead moves *into* the punch so as to decrease the duration of impact by half, by how much will the force of impact be increased?
3. A boxer being hit with a punch contrives to extend time for best results, whereas a karate expert delivers a force in a short time for best results. Isn't there a contradiction here?
4. When does impulse equal momentum?

Check Your Answers

1. The force of impact will be only a third of what it would have been if he hadn't pulled back.
2. The force of impact will be 2 times greater than it would have been if he had held his head still. Impacts of this kind account for many knockouts.
3. There is no contradiction because the best results for each are quite different. The best result for the boxer is reduced force, accomplished by maximizing time, and the best result for the karate expert is increased force delivered in minimum time.
4. Generally, impulse equals a *change* in momentum. If the initial momentum of an object is zero when the impulse is applied, then impulse = final momentum. And, if an object is brought to rest, impulse = initial momentum.

Bouncing

A flowerpot dropped onto your head bounces quickly. Ouch! If bouncing took a longer time, as with a safety net, then the force of the bounce would be much smaller.

If a flowerpot falls from a shelf onto your head, you may be in trouble. If it bounces from your head, you may be in more serious trouble. Why? Because impulses are greater when an object bounces. The impulse required to bring an object to a stop and then to "throw it back again" is greater than the impulse required merely to bring the object to a stop. Suppose, for example, that you catch the falling pot with your hands. You provide an impulse to reduce its momentum to zero. If you throw the pot upward again, you have to provide additional impulse. This increased amount of impulse is the same that your head supplies if the flowerpot bounces from it.

The left opening photo at the beginning of this chapter shows physics instructor Howie Brand swinging a dart against a wooden block. When the dart has a nail at its nose, the dart comes to a halt as it sticks to the block. The block remains upright.

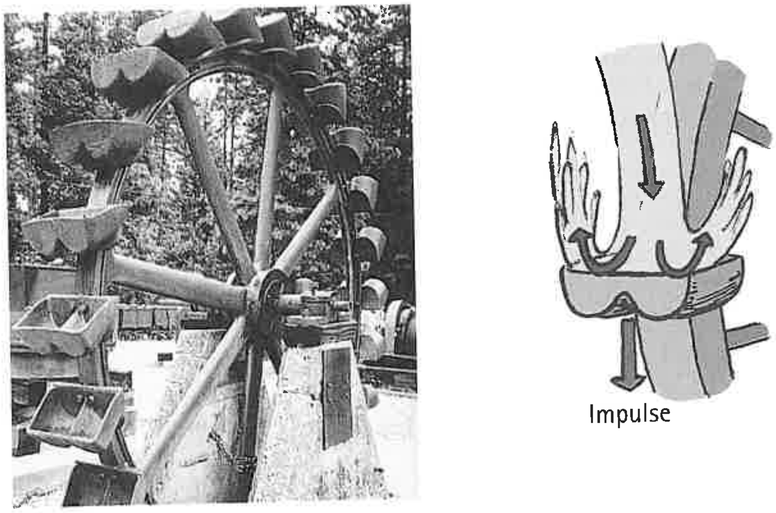

FIGURE 6.10

Another view of a Pelton wheel. The curved blades cause water to bounce and make a U-turn, which produces a greater impulse to turn the wheel.

When the nail is removed and the nose of the dart is half of a solid rubber ball, the dart bounces upon contact with the block. The block topples over. The force against the block is greater when bouncing occurs.

The fact that impulses are greater when bouncing occurs was used with great success during the California Gold Rush, as discussed at the beginning of the chapter. Pelton designed a curved paddle that caused the incoming water to bounce upon impact, increasing the impulse on the wheel.

CHECK POINT

1. In reference to Figure 6.9, how does the force that Cassy exerts on the bricks compare with the force exerted on her hand?
2. How will the impulse resulting from the impact differ if her hand bounces back upon striking the bricks?

Check Your Answers

1. In accord with Newton's third law, the forces will be equal. Only the resilience of the human hand and the training she has undergone to toughen her hand allow this feat to be performed without broken bones.
2. The impulse will be greater if her hand bounces from the bricks upon impact. If the time of impact is not correspondingly increased, a greater force is then exerted on the bricks (and her hand!).

Conservation of Momentum

From Newton's second law, you know that to accelerate an object, a net force must be applied to it. This chapter states much the same thing, but in different language. If you wish to change the momentum of an object, exert an impulse on it.

Only an impulse external to a system can change the momentum of the system. Internal forces and impulses won't work. For example, the molecular forces within a baseball have no effect on the momentum of the baseball, just as a push against the dashboard of a car you're sitting in does not affect the momentum of the car. Molecular forces within the baseball and a push on the dashboard are internal forces. They come in balanced pairs that cancel to zero within the object. To change the momentum of the ball or the car, an external push or pull is required. If no external force is present, then no external impulse is present, and no change in momentum is possible.

As another example, consider the cannon being fired in Figure 6.11. The force on the cannonball inside the cannon barrel is equal and opposite to the force causing the cannon to recoil. Since these forces act for the same time, the impulses are also equal and opposite. Recall Newton's third law about action and reaction forces. It applies to impulses, too. These impulses are internal to the system comprising the cannon and the cannonball, so they don't change the momentum of the

Momentum is conserved for all collisions, elastic and inelastic (whenever external forces don't interfere).

fyi

- In Figure 6.11, most of the cannonball's momentum is in speed; most of the recoiling cannon's momentum is in mass. So $mV = \mathcal{M}v$.

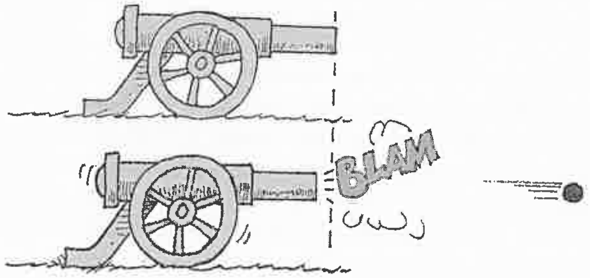

FIGURE 6.11

INTERACTIVE FIGURE

The momentum before firing is zero. After firing, the net momentum is still zero, because the momentum of the cannon is equal and opposite to the momentum of the cannonball.

cannon–cannonball system. Before the firing, the system is at rest and the momentum is zero. After the firing, the net momentum, or total momentum, is *still* zero. Net momentum is neither gained nor lost.

Momentum, like the quantities velocity and force, has both direction and magnitude. It is a *vector quantity.* Like velocity and force, momentum can be cancelled. So, although the cannonball in the preceding example gains momentum when fired and the recoiling cannon gains momentum in the opposite direction, there is no gain in the cannon–cannonball *system.* The momenta (plural form of momentum) of the cannonball and the cannon are equal in magnitude and opposite in direction.[2] Therefore, these momenta cancel to zero for the system as a whole. Since no net external force acts on the system, there is no net impulse on the system and no net change in momentum. You can see that, *if no net force or net impulse acts on a system, the momentum of that system cannot change.*

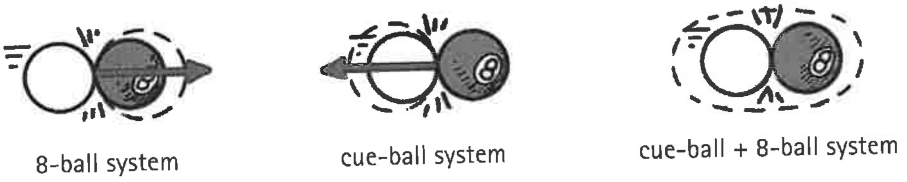

FIGURE 6.12

A cue ball hits an 8 ball head-on. Consider this event in three systems: (a) An external force acts on the 8-ball system, and its momentum increases. (b) An external force acts on the cue-ball system, and its momentum decreases. (c) No external force acts on the cue-ball + 8-ball system, and momentum is conserved (simply transferred from one part of the system to the other).

When momentum, or any quantity in physics, does not change, we say it is *conserved.* The idea that momentum is conserved when no external force acts is elevated to a central law of mechanics, called the **law of conservation of momentum,** which states:

In the absence of an external force, the momentum of a system remains unchanged.

In any system wherein all forces are internal—as, for example, cars colliding, atomic nuclei undergoing radioactive decay, or stars exploding—the net momentum of the system before and after the event is the same.

Can you see how Newton's laws relate to momentum conservation?

CHECK POINT

1. Newton's second law states that, if no net force is exerted on a system, no acceleration occurs. Does it follow that no change in momentum occurs?
2. Newton's third law states that the force a cannon exerts on a cannonball is equal and opposite to the force the cannonball exerts on the cannon. Does it follow that the *impulse* the cannon exerts on the cannonball is equal and opposite to the *impulse* the cannonball exerts on the cannon?

Check Your Answers

1. Yes, because no acceleration means that no change occurs in velocity or in momentum (mass × velocity). Another line of reasoning is simply that no net force means there is no net impulse and thus no change in momentum.
2. Yes, because the interaction between both occurs during the same *time* interval. Since time is equal and the forces are equal and opposite, the impulses, *Ft*, are also equal and opposite. Impulse is a vector quantity and can be cancelled.

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[2] Here we neglect the momentum of ejected gases from the exploding gunpowder, which can be considerable. Firing a gun with blanks at close range is a definite no-no because of the considerable momentum of ejecting gases. More than one person has been killed by close-range firing of blanks. In 1998, a minister in Jacksonville, Florida, dramatizing his sermon before several hundred parishioners, including his family, shot himself in the head with a blank round from a .357-caliber Magnum. Although no slug emerged from the gun, exhaust gases did—enough to be lethal. So, strictly speaking, the momentum of the bullet + the momentum of the exhaust gases is equal to the opposite momentum of the recoiling gun.

Conservation Laws

A conservation law specifies that certain quantities in a system remain precisely constant, regardless of what changes may occur within the system. It is a law of constancy during change. In this chapter, we see that momentum is unchanged during collisions. We say that momentum is conserved. In the next chapter, we'll learn that energy is conserved as it transforms—the amount of energy in light, for example, transforms completely to thermal energy when the light is absorbed. We'll see, in Chapter 8, that angular momentum is conserved—whatever the rotational motion of a planetary system, its angular momentum remains unchanged so long as it is free of outside influences. In Chapter 22, we'll learn that electric charge is conserved, which means that it can neither be created nor destroyed. When we study nuclear physics, we'll see that these and other conservation laws rule in the submicroscopic world. Conservation laws are a source of deep insights into the simple regularity of nature and are often considered the most fundamental of physical laws. Can you think of things in your own life that remain constant as other things change?

Collisions

Momentum is conserved in collisions—that is, the net momentum of a system of colliding objects is unchanged before, during, and after the collision. This is because the forces that act during the collision are internal forces—forces acting and reacting within the system itself. There is only a redistribution or sharing of whatever momentum exists before the collision. In any collision, we can say

Net momentum before collision = net momentum after collision.

This is true no matter how the objects might be moving before they collide.

When a moving billiard ball makes a head-on collision with another billiard ball at rest, the moving ball comes to rest and the other ball moves with the speed of the colliding ball. We call this an **elastic collision;** ideally, the colliding objects rebound without lasting deformation or the generation of heat (Figure 6.13). But momentum is conserved even when the colliding objects become entangled during the collision. This is an **inelastic collision,** characterized by deformation, or the generation of heat, or both. In a perfectly inelastic collision, both objects stick together. Consider, for example, the case of a freight car moving along a track and colliding with another freight car at rest (Figure 6.14). If the freight cars are of equal mass and are coupled by the collision, can we predict the velocity of the coupled cars after impact?

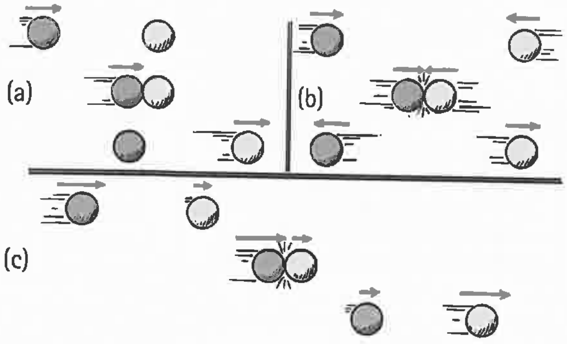


FIGURE 6.13

INTERACTIVE FIGURE

Elastic collisions of equally massive balls. (a) A green ball strikes a yellow ball at rest. (b) A head-on collision. (c) A collision of balls moving in the same direction. In each case, momentum is transferred from one ball to the other.

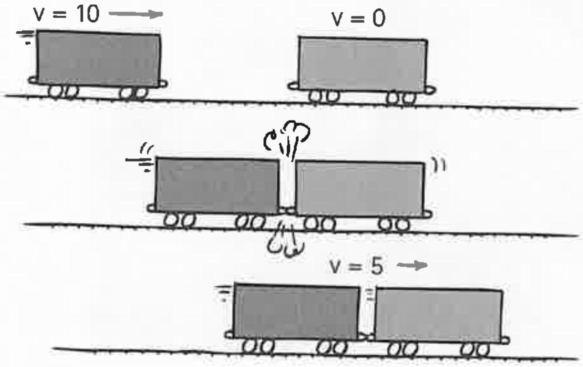


FIGURE 6.14

INTERACTIVE FIGURE

Inelastic collision. The momentum of the freight car on the left is shared with the same-mass freight car on the right after collision.

Suppose the single car is moving at 10 meters per second (m/s), and we consider the mass of each car to be *m*. Then, from the conservation of momentum,

$$(\text{net } mv)_{\text{before}} = (\text{net } mv)_{\text{after}}$$

$$(m \times 10)_{\text{before}} = (2m \times V)_{\text{after}}$$

By simple algebra, $V = 5$ m/s. This makes sense because, since twice as much mass is moving after the collision, the velocity must be half as much as the velocity before collision. Both sides of the equation are then equal.

Note the inelastic collisions shown in Figure 6.15. If A and B are moving with equal momenta in opposite directions (A and B colliding head-on), then one of these is considered to be negative, and the momenta add algebraically to zero. After collision, the coupled wreck remains at the point of impact, with zero momentum.

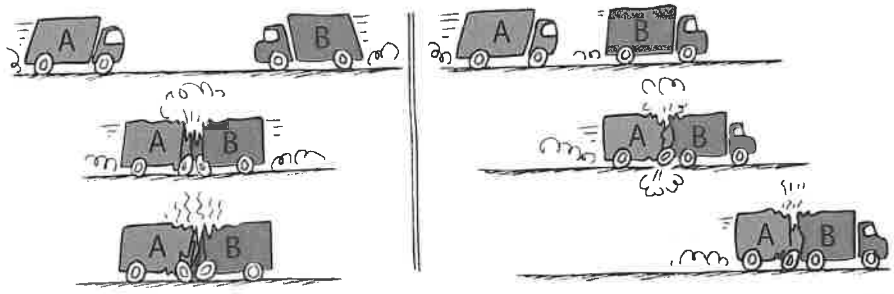


FIGURE 6.15

INTERACTIVE FIGURE

Inelastic collisions. The net momentum of the trucks before and after collision is the same.

If, on the other hand, A and B are moving in the same direction (A catching up with B), the net momentum is simply the addition of their individual momenta.

If A, however, moves east with, say, 10 more units of momentum than B moving west (not shown in the figure), after collision, the coupled wreck moves east with 10 units of momentum. The wreck will finally come to a rest, of course, because of the external force of friction by the ground. The time of impact is short, however, and the impact force of the collision is so much greater than the external friction force that momentum immediately before and after the collision is, for practical purposes, conserved. The net momentum just before the trucks collide (10 units) is equal to the combined momentum of the crumpled trucks just after impact (10 units). The same principle applies to gently docking spacecraft, where friction is entirely absent. Their net momentum just before docking is preserved as their net momentum just after docking.

Galileo worked hard to produce smooth surfaces to minimize friction. How he would have loved to experiment with today's air tracks!

FIGURE 6.16

Will Maynez demonstrates his air track. Blasts of air from tiny holes provide a friction-free surface for the carts to glide upon.

CHECK POINT

Consider the air track in Figure 6.16. Suppose a gliding cart with a mass of 0.5 kg bumps into, and sticks to, a stationary cart that has a mass of 1.5 kg. If the speed of the gliding cart before impact is v_{before}, how fast will the coupled carts glide after collision?

Check Your Answer

According to momentum conservation, the momentum of the 0.5-kg cart before the collision = momentum of both carts stuck together afterwards.

$$0.5v_{\text{before}} = (0.5 + 1.5)\,v_{\text{after}}$$

$$v_{\text{after}} = \frac{0.5\,v_{\text{before}}}{(0.5 + 1.5)} = \frac{0.5\,v_{\text{before}}}{2} = \frac{v_{\text{before}}}{4}$$

This makes sense, because four times as much mass will be moving after the collision, so the coupled carts will glide more slowly. The same momentum means four times the mass glides 1/4 as fast.

For a numerical example of momentum conservation, consider a fish that swims toward and swallows a smaller fish at rest (Figure 6.17). If the larger fish has a mass of 5 kg and swims 1 m/s toward a 1-kg fish, what is the velocity of the larger fish immediately after lunch? Neglect the effects of water resistance.

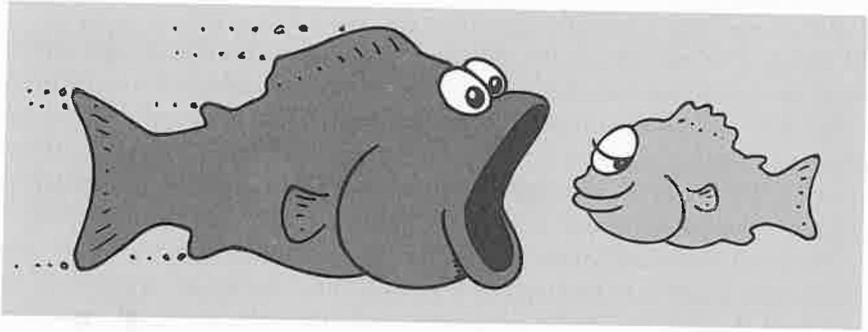


FIGURE 6.17
Two fish make up a system, which has the same momentum just before lunch and just after lunch.

$$\begin{aligned}\text{Net momentum before lunch} &= \text{net momentum after lunch}\\ (5\text{ kg})(1\text{ m/s}) + (1\text{ kg})(0\text{ m/s}) &= (5\text{ kg} + 1\text{ kg})\,v\\ 5\text{ kg}\cdot\text{m/s} &= (6\text{ kg})\,v\\ v &= 5/6\text{ m/s}\end{aligned}$$

Here we see that the small fish has no momentum before lunch because its velocity is zero. After lunch, the combined mass of both fishes moves at velocity v, which, by simple algebra, is seen to be 5/6 m/s. This velocity is in the same direction as that of the larger fish.

Suppose the small fish in this example is not at rest, but swims toward the left at a velocity of 4 m/s. It swims in a direction opposite that of the larger fish—a negative direction, if the direction of the larger fish is considered positive. In this case,

$$\begin{aligned}\text{Net momentum before lunch} &= \text{net momentum after lunch}\\ (5\text{ kg})(1\text{ m/s}) + (1\text{ kg})(-4\text{ m/s}) &= (5\text{ kg} + 1\text{ kg})\,v\\ (5\text{ kg}\cdot\text{m/s}) - (4\text{ kg}\cdot\text{m/s}) &= (6\text{ kg})\,v\\ 1\text{ kg}\cdot\text{m/s} &= 6\text{ kg}\,v\\ v &= 1/6\text{ m/s}\end{aligned}$$

Note that the negative momentum of the smaller fish before lunch effectively slows the larger fish after lunch. If the smaller fish were swimming twice as fast, then

$$\begin{aligned} \text{Net momentum before lunch} &= \text{net momentum after lunch} \\ (5\text{ kg})(1\text{ m/s}) + (1\text{ kg})(-8\text{ m/s}) &= (5\text{ kg} + 1\text{ kg})\, v \\ (5\text{ kg}\cdot\text{m/s}) - (8\text{ kg}\cdot\text{m/s}) &= (6\text{ kg})\, v \\ -3\text{ kg}\cdot\text{m/s} &= 6\text{ kg}\, v \\ v &= -1/2\text{ m/s} \end{aligned}$$

Here we see the final velocity is $-1/2$ m/s. What is the significance of the minus sign? It means that the final velocity is *opposite* to the initial velocity of the larger fish. After lunch, the two-fish system moves toward the left. We leave as a chapter-end problem finding the initial velocity of the smaller fish to halt the larger fish in its tracks.

More Complicated Collisions

The net momentum remains unchanged in any collision, regardless of the angle between the paths of the colliding objects. Expressing the net momentum when different directions are involved can be achieved with the parallelogram rule of vector addition. We will not treat such complicated cases in great detail here, but will show some simple examples to convey the concept.

Unlike billiard balls after a collision, nuclear particles experience no air drag or other friction and fly on in straight lines without losing speed until hitting another particle or undergoing radioactive decay.

In Figure 6.18, we see a collision between two cars traveling at right angles to each other. Car A has a momentum directed due east, and car B's momentum is directed due north. If their individual momenta are equal in magnitude, then their combined momentum is in a northeasterly direction. This is the direction the coupled cars will travel after collision. We see that, just as the diagonal of a square is not equal to the sum of two of the sides, the magnitude of the resulting momentum will not simply equal the arithmetic sum of the two momenta before collision. Recall the relationship between the diagonal of a square and the length of one of its sides, Figure 5.23 in Chapter 5—the diagonal is $\sqrt{2}$ times the length of the side of a square. So, in this example, the magnitude of the resultant momentum will be equal to $\sqrt{2}$ times the momentum of either vehicle.

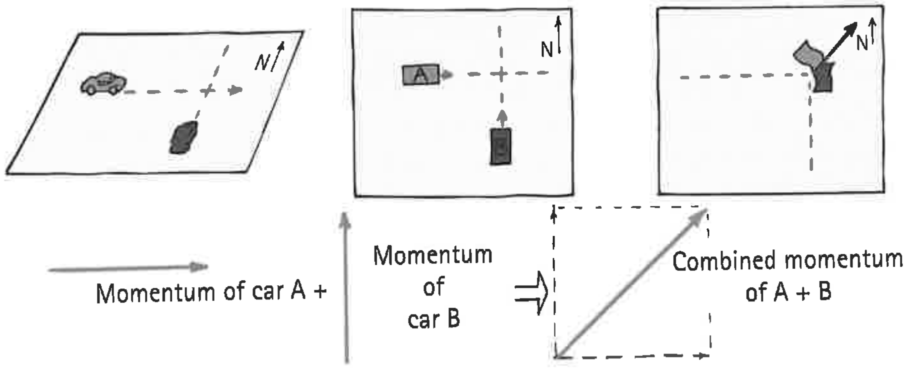


FIGURE 6.18

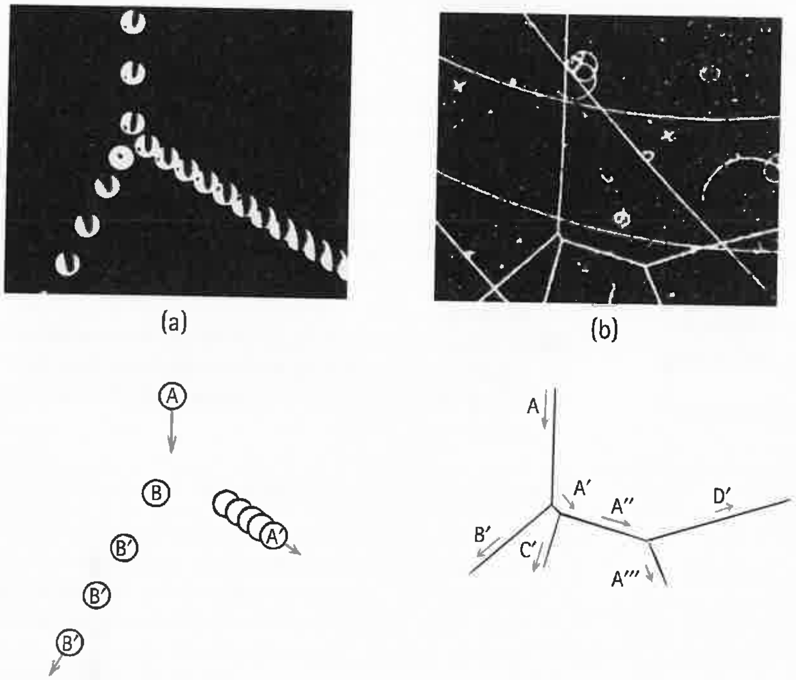
INTERACTIVE FIGURE

Momentum is a vector quantity.

Figure 6.20 shows a falling Fourth-of-July firecracker exploding into two pieces. The momenta of the fragments combine by vector addition to equal the original momentum of the falling firecracker. Figure 6.19b extends this idea to the microscopic realm, where the tracks of subatomic particles are revealed in a liquid hydrogen bubble chamber.

Whatever the nature of a collision or however complicated it is, the total momentum before, during, and after remains unchanged. This extremely useful law enables us to learn much from collisions without knowing any details about the forces that act in the collision. We will see, in the next chapter, that energy, perhaps in multiple forms, is also conserved. By applying momentum and energy conservation to the collisions of subatomic particles as observed in various detection chambers, we can compute the masses of these tiny particles. We obtain this information by measuring momenta and energy before and after collisions. Remarkably, this achievement is possible without any exact knowledge of the forces that act.

Conservation of momentum and conservation of energy (which we will cover in the next chapter) are the two most powerful tools of mechanics. Applying them yields detailed information that ranges from facts about the interactions of subatomic particles to the structure and motion of entire galaxies.


(a)

(b)

FIGURE 6.19

Momentum is conserved for colliding billiard balls and for colliding nuclear particles in a liquid hydrogen bubble chamber. In (a), billiard ball A strikes billiard ball B, which was initially at rest. In (b), proton A collides successively with protons B, C, and D. The moving protons leave tracks of tiny bubbles.

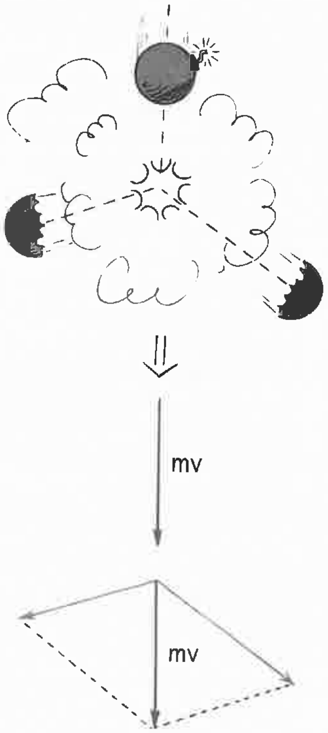


FIGURE 6.20

After the firecracker bursts, the momenta of its fragments add up (by vector addition) to the original momentum.

SUMMARY OF TERMS

Momentum The product of the mass of an object and its velocity.

Impulse The product of the force acting on an object and the time during which it acts.

Relationship of impulse and momentum Impulse is equal to the change in the momentum of the object that the impulse acts upon. In symbol notation,

$$Ft = \Delta mv$$

Law of conservation of momentum In the absence of an external force, the momentum of a system remains unchanged. Hence, the momentum before an event involving only internal forces is equal to the momentum after the event:

$$mv_{\text{(before event)}} = mv_{\text{(after event)}}$$

Elastic collision A collision in which colliding objects rebound without lasting deformation or the generation of heat.

Inelastic collision A collision in which the colliding objects become distorted, generate heat, and possibly stick together.

REVIEW QUESTIONS

Momentum

1. Which has a greater momentum, a heavy truck at rest or a moving skateboard?

Impulse

2. How does impulse differ from force?
3. What are the two ways to increase impulse?
4. For the same force, why does a long cannon impart more speed to a cannonball than a small cannon?

Impulse Changes Momentum

5. Is the impulse–momentum relationship related to Newton's second law?
6. To impart the greatest momentum to an object, should you exert the largest force possible, extend that force for as long a time as possible, or both? Explain.
7. When you are in the way of a moving object and an impact force is your fate, are you better off decreasing its momentum over a short time or over a long time? Explain.
8. Why is it a good idea to have your hand extended forward when you are getting ready to catch a fast-moving baseball with your bare hand?
9. Why would it be a poor idea to have the back of your hand up against the outfield wall when you catch a long fly ball?
10. In karate, why is a force that is applied for a short time more advantageous?
11. In boxing, why is it advantageous to roll with the punch?

Bouncing

12. Which undergoes the greatest change in momentum: (1) a baseball that is caught, (2) a baseball that is thrown, or (3) a baseball that is caught and then thrown back, if all of the baseballs have the same speed just before being caught and just after being thrown?
13. In the preceding question, in which case is the greatest impulse required?

Conservation of Momentum

14. Can you produce a net impulse on an automobile by sitting inside and pushing on the dashboard? Can the internal forces within a soccer ball produce an impulse on the soccer ball that will change its momentum?
15. Is it correct to say that, if no net impulse is exerted on a system, then no change in the momentum of the system will occur?
16. What does it mean to say that momentum (or any quantity) is *conserved?*
17. When a cannonball is fired, momentum is conserved for the *system* of cannon plus cannonball. Would momentum be conserved for the system if momentum were not a vector quantity? Explain.

Collisions

18. Distinguish between an *elastic collision* and an *inelastic collision.* For which type of collision is momentum conserved?
19. Railroad car A rolls at a certain speed and makes a perfectly elastic collision with car B of the same mass. After the collision, car A is observed to be at rest. How does the speed of car B compare with the initial speed of car A?
20. If the equally massive cars of the previous question stick together after colliding inelastically, how does their speed after the collision compare with the initial speed of car A?

More Complicated Collisions

21. Suppose a ball of putty moving horizontally with 1 kg·m/s of momentum collides and sticks to an identical ball of putty moving vertically with 1 kg·m/s of momentum. Why is their combined momentum not simply the arithmetic sum, 2 kg·m/s?
22. In the preceding question, what is the total momentum of the balls of putty before and after the collision?

PLUG AND CHUG

Momentum = mv

1. What is the momentum of an 8-kg bowling ball rolling at 2 m/s?
2. What is the momentum of a 50-kg carton that slides at 4 m/s across an icy surface?

Impulse = Ft

3. What impulse occurs when an average force of 10 N is exerted on a cart for 2.5 s?
4. What impulse occurs when the same force of 10 N acts on the cart for twice the time?

Impulse = change in momentum: $Ft = \Delta mv$

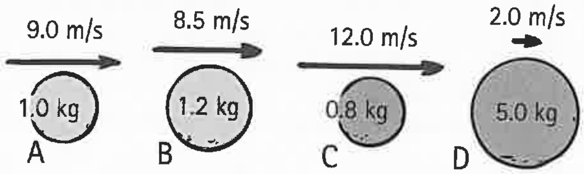
5. What is the impulse on an 8-kg ball rolling at 2 m/s when it bumps into a pillow and stops?
6. How much impulse stops a 50-kg carton sliding at 4 m/s when it meets a rough surface?

Conservation of momentum: $mv_{\text{before}} = mv_{\text{after}}$

7. A 2-kg blob of putty moving at 3 m/s slams into a 2-kg blob of putty at rest. Calculate the speed of the two stuck-together blobs of putty immediately after colliding.
8. Calculate the speed of the two blobs if the one at rest is 4 g.

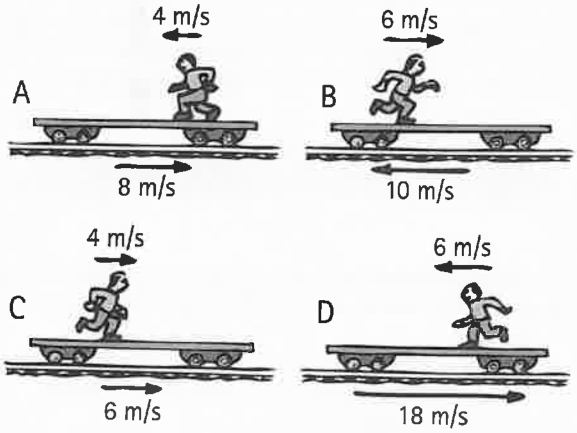
RANKING

1. The balls have different masses and speeds. Rank the following from greatest to least.



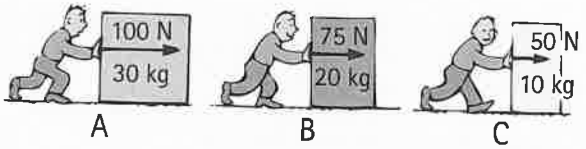
   a. Momentum
   b. The impulses needed to stop the balls

2. Jogging Jake runs along a train flatcar that moves at the velocities shown. In each case, Jake's velocity is given relative to the car. Call direction to the right positive. Rank the following from greatest to least.



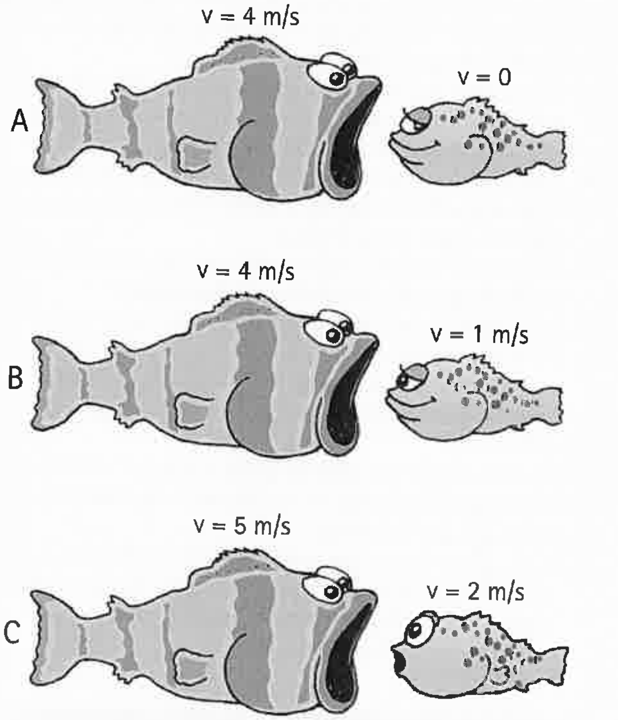
   a. The magnitude of Jake's momentum relative to the flatcar
   b. Jake's momentum relative to an observer at rest on the ground

3. Marshall pushes crates starting from rest across the floor of his classroom for 3 s with a net force as shown. For each crate, rank the following from greatest to least.

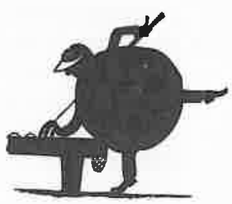


   a. Impulse delivered
   b. Change in momentum
   c. Final speed
   d. Momentum in 3 s

4. A hungry fish is about to have lunch at the speeds shown. Assume the hungry fish has a mass 5 times that of the small fish. Immediately after lunch, for each case, rank from greatest to least the speed of the formerly hungry fish.



PROJECT

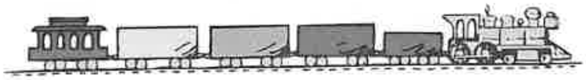


When you get a bit ahead in your studies, cut classes some afternoon and visit your local pool or billiards parlor and bone up on momentum conservation. Note that no matter how complicated the collision of balls, the momentum along the line of action of the cue ball before impact is the same as the combined momentum of all the balls along this direction after impact and that the components of momenta perpendicular to this line of action cancel to zero after impact, the same value as before impact in this direction. You'll see both the vector nature of momentum and its conservation more clearly when rotational skidding—"English"—is not imparted to the cue ball. When English is imparted by striking the cue ball off center, rotational momentum, which is also conserved, somewhat complicates analysis. But, regardless of how the cue ball is struck, in the absence of external forces, both linear and rotational momenta are always conserved. Both pool and billiards offer a first-rate exhibition of momentum conservation in action.

EXERCISES

1. When a supertanker is brought to a stop, its engines are typically cut off about 25 km from port. Why is it so difficult to stop or turn a supertanker?
2. In terms of impulse and momentum, why do padded dashboards make automobiles safer?
3. In terms of impulse and momentum, why do air bags in cars reduce the chances of injury in accidents?
4. Why do gymnasts use floor mats that are very thick?
5. In terms of impulse and momentum, why are nylon ropes, which stretch considerably under tension, favored by mountain climbers?
6. Why is it a serious folly for a bungee jumper to use a steel cable rather than an elastic cord?
7. When jumping from a significant height, why is it advantageous to land with your knees bent?
8. A person can survive a feet-first impact at a speed of about 12 m/s (27 mi/h) on concrete; 15 m/s (34 mi/h) on soil; and 34 m/s (76 mi/h) on water. Why the different values for different surfaces?
9. When catching a foul ball at a baseball game, why is it important to extend your bare hands upward so they can move downward as the ball is being caught?
10. Automobiles in past times were manufactured to be as rigid as possible, whereas modern autos are designed to crumple upon impact. Why?
11. In terms of impulse and momentum, why is it important that helicopter blades deflect air downward?
12. It is generally much more difficult to stop a heavy truck than a skateboard when they move at the same speed. State a case in which the moving skateboard could require more stopping force. (Consider relative times.)
13. A lunar vehicle is tested on Earth at a speed of 10 km/h. When it travels as fast on the Moon, is its momentum more, less, or the same?
14. If you throw a raw egg against a wall, you'll break it. But when Peter Hopkinson throws an egg at the same speed into a sagging sheet, it doesn't break. Explain, using concepts from this chapter.

15. Why is it difficult for a firefighter to hold a hose that ejects large amounts of water at a high speed?
16. Would you care to fire a gun that has a bullet 10 times as massive as the gun? Explain.
17. Why are the impulses that colliding objects exert on each other equal and opposite?
18. If a ball is projected upward from the ground with 10 kg·m/s of momentum, what is Earth's momentum of recoil? Why do we not feel this?
19. When an apple falls from a tree and strikes the ground without bouncing, what becomes of its momentum?
20. Why does a baseball catcher's mitt have more padding than a conventional glove?
21. Why do 8-ounce boxing gloves hit harder than 16-ounce gloves?
22. A boxer can punch a heavy bag for more than an hour without tiring but will tire quickly when boxing with an opponent for a few minutes. Why? (*Hint:* When the boxer's fist is aimed at the bag, what supplies the impulse to stop the punches? When the boxer's fist is aimed at the opponent, what or who supplies the impulse to stop the punches that don't connect?)
23. Railroad cars are loosely coupled so that there is a noticeable time delay from the time the first car is moved until the last cars are moved from rest by the locomotive. Discuss the advisability of this loose coupling and slack between cars from the point of view of impulse and momentum.



24. If only an external force can change the velocity of a body, how can the internal force of the brakes bring a moving car to rest?
25. You are at the front of a floating canoe near a dock. You jump, expecting to land on the dock easily. Instead you land in the water. Explain.
26. Explain how a swarm of flying insects can have a net momentum of zero.
27. A fully dressed person is at rest in the middle of a pond on perfectly frictionless ice and must get to shore. How can this be accomplished?
28. If you throw a ball horizontally while standing on roller skates, you roll backward with a momentum that matches that of the ball. Will you roll backward if you go through the motions of throwing the ball, but instead hold on to it? Explain.
29. The examples of the two previous exercises can be explained in terms of momentum conservation and in terms of Newton's third law. Assuming you've answered them in terms of momentum conservation, answer them also in terms of Newton's third law (or vice versa, if you answered already in terms of Newton's third law).
30. In Chapter 5, rocket propulsion was explained in terms of Newton's third law. That is, the force that propels a rocket is from the exhaust gases pushing against the rocket, the reaction to the force the rocket exerts on the exhaust gases. Explain rocket propulsion in terms of momentum conservation.
31. Explain how the conservation of momentum is a consequence of Newton's third law.
32. Go back to Exercise 23 in Chapter 5 and answer it in terms of momentum conservation.

33. If you place a box on an inclined plane, it gains momentum as it slides down. What is responsible for this change in momentum?

34. Your friend says that the law of momentum conservation is violated when a ball rolls down a hill and gains momentum. What do you say?

35. What is meant by a system, and how is it related to the conservation of momentum?

36. If you toss a ball upward, is the momentum of the moving ball conserved? Is the momentum of the system consisting of ball + Earth conserved? Explain your answers.

37. The momentum of an apple falling to the ground is not conserved because the external force of gravity acts on it. But momentum is conserved in a larger system. Explain.

38. Drop a stone from the top of a high cliff. Identify the system wherein the net momentum is zero as the stone falls.

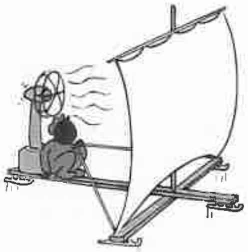
39. A car hurtles off a cliff and crashes on the canyon floor below. Identify the system wherein the net momentum is zero during the crash.

40. Bronco dives from a hovering helicopter and finds his momentum increasing. Does this violate the conservation of momentum? Explain.

41. Which exerts the greater impulse on a steel plate—machine gun bullets that bounce from the plate, or the same bullets squashing and sticking to the plate?

42. An ice sailcraft is stalled on a frozen lake on a windless day. The skipper sets up a fan as shown. If all the wind bounces backward from the sail, will the craft be set in motion? If so, in what direction?

43. Will your answer to the preceding exercise be different if the air is brought to a halt by the sail without bouncing?



44. Discuss the advisability of simply removing the sail in the preceding exercises.

45. As you toss a ball upward, is there a change in the normal force on your feet? Is there a change when you catch the ball? (Think of doing this while standing on a bathroom scale.)

46. When you are traveling in your car at highway speed, the momentum of a bug is suddenly changed as it splatters onto your windshield. Compared with the change in momentum of the bug, by how much does the momentum of your car change?

47. If a tennis ball and a bowling ball collide in midair, does each undergo the same amount of momentum change? Defend your answer.

48. If a Mack truck and a MiniCooper have a head-on collision, which vehicle will experience the greater force of impact? The greater impulse? The greater change in momentum? The greater deceleration?

49. Would a head-on collision between two cars be more damaging to the occupants if the cars stuck together or if the cars rebounded upon impact?

50. Freddy Frog drops vertically from a tree onto a horizontally moving skateboard. The skateboard slows. Give two reasons for this, one in terms of a horizontal friction force between Freddy's feet and the skateboard, and one in terms of momentum conservation.

51. A 0.5-kg cart on an air track moves 1.0 m/s to the right, heading toward a 0.8-kg cart moving to the left at 1.2 m/s. What is the direction of the two-cart system's momentum?

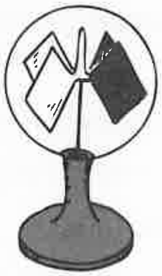
52. In a movie, the hero jumps straight down from a bridge onto a small boat that continues to move with no change in velocity. What physics is being violated here?

53. To throw a ball, do you exert an impulse on it? Do you exert an impulse to catch it at the same speed? About how much impulse do you exert, in comparison, if you catch it and immediately throw it back again? (Imagine yourself on a skateboard.)

54. Suppose that there are three astronauts outside a spaceship and that they decide to play catch. All the astronauts weigh the same on Earth and are equally strong. The first astronaut throws the second one toward the third one and the game begins. Describe the motion of the astronauts as the game proceeds. How long will the game last?

55. In reference to Figure 6.9, how will the impulse at impact differ if Cassy's hand bounces back upon striking the bricks? In any case, how does the force exerted on the bricks compare to the force exerted on her hand?

56. Light possesses momentum. This can be demonstrated with a radiometer, shown in the sketch. Metal vanes painted black on one side and white on the other are free to rotate around the point of a needle mounted in a vacuum. When light is incident on the black surface, it is absorbed; when light is incident upon the white surface, it is reflected. Upon which surface is the impulse of incident light greater, and which way will the vanes rotate? (They rotate in the opposite direction in the more common radiometers in which air is present in the glass chamber; your instructor may tell you why.)



57. A deuteron is a nuclear particle of unique mass made up of one proton and one neutron. Suppose that a deuteron is accelerated up to a certain very high speed in a cyclotron and directed into an observation chamber, where it collides with and sticks to a target particle that is initially at rest and then is observed to move at exactly half the speed of the incident deuteron. Why do the observers state that the target particle is itself a deuteron?

58. A billiard ball will stop short when it collides head-on with a ball at rest. The ball cannot stop short, however, if the collision is not exactly head-on—that is, if the second ball moves at an angle to the path of the first. Do you know why? (*Hint:* Consider momentum before and after the collision along the initial direction of the first ball and also in a direction perpendicular to this initial direction.)

59. When a stationary uranium nucleus undergoes fission, it breaks into two unequal chunks that fly apart. What can you conclude about the momenta of the chunks? What can you conclude about the relative speeds of the chunks?

60. You have a friend who says that after a golf ball collides with a bowling ball at rest, although the speed gained by the bowling ball is very small, its momentum exceeds the initial momentum of the golf ball. Your friend further asserts this is related to the "negative" momentum of the golf ball after collision. Another friend says this is hogwash—that momentum conservation would be violated. Which friend do you agree with?

PROBLEMS

1. When bowling, your physics buddy asks how much impulse is needed to stop a 10-kg bowling ball moving at 6 m/s. What is your answer?

2. Joanne drives her car with a mass of 1000 kg at a speed of 20 m/s. Show that to bring her car to a halt in 10 s road friction must exert a force of 2000 N on the car.

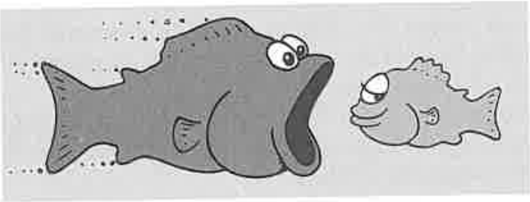
3. A car carrying a 75-kg test dummy crashes into a wall at 25 m/s and is brought to rest in 0.1 s. Show that the average force exerted by the seat belt on the dummy is 18,750 N.

4. Judy (mass 40 kg), standing on slippery ice, catches her leaping dog (mass 15 kg) moving horizontally at 3.0 m/s. Show that the speed of Judy and her dog after the catch is 0.8 m/s.

5. A 2-kg ball of putty moving to the right has a head-on inelastic collision with a 1-kg putty ball moving to the left. If the combined blob doesn't move just after the collision, what can you conclude about the relative speeds of the balls before they collided?

6. A railroad diesel engine weighs four times as much as a freight car. If the diesel engine coasts at 5 km/h into a freight car that is initially at rest, show that the speed of the coupled cars is 4 km/h.

7. A 5-kg fish swimming 1 m/s swallows an absentminded 1-kg fish swimming toward it at a speed that brings both fish to a halt immediately after lunch. Show that the speed of the approaching smaller fish before lunch must have been 5 m/s.



8. Comic-strip hero Superman meets an asteroid in outer space and hurls it at 800 m/s, as fast as a bullet. The asteroid is a thousand times more massive than Superman. In the strip, Superman is seen at rest after the throw. Taking physics into account, what would be his recoil velocity?

9. Two automobiles, each of mass 1000 kg, are moving at the same speed, 20 m/s, when they collide and stick together. In what direction and at what speed does the wreckage move (a) if one car was driving north and one south; (b) if one car was driving north and one east (as shown in Figure 6.18)?

•10. An ostrich egg of mass m is tossed at a speed v into a sagging bed sheet and is brought to rest in a time t.

a. Show that the force acting on the egg when it hits the sheet is mv/t.

b. If the mass of the egg is 1 kg, its initial speed is 2 m/s, and the time to stop is 0.2 s, show that the average force on the egg is 10 N.

CHAPTER 6 ONLINE RESOURCES

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Interactive Figures

- 6.11, 6.13, 6.14, 6.15, 6.18

Tutorial

- Newton's Third Law and Momentum

Videos

- Definition of Momentum
- Changing Momentum: Follow-through
- Decreasing Momentum Over a Short Time

Quizzes

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