Forces exerted by Earth, wind, and water, properly channeled by the strength and skill of these windsurfers, combine to create a non-zero net force on their surfboards, driving them forward through the waves.

4.1 Forces

4.2 Newton’s First Law

4.3 Newton’s Second Law

4.4 Newton’s Third Law

4.5 Applications of Newton’s Laws

4.6 Forces of Friction

THE LAWS OF MOTION

Classical mechanics describes the relationship between the motion of objects found in our everyday world and the forces acting on them. As long as the system under study doesn’t involve objects comparable in size to an atom or traveling close to the speed of light, classical mechanics provides an excellent description of nature.

This chapter introduces Newton’s three laws of motion and his law of gravity. The three laws are simple and sensible. The first law states that a force must be applied to an object in order to change its velocity. Changing an object’s velocity means accelerating it, which implies a relationship between force and acceleration. This relationship, the second law, states that the net force on an object equals the object’s mass times its acceleration. Finally, the third law says that whenever we push on something, it pushes back with equal force in the opposite direction. These are the three laws in a nutshell.

Newton’s three laws, together with his invention of calculus, opened avenues of inquiry and discovery that are used routinely today in virtually all areas of mathematics, science, engineering, and technology. Newton’s theory of universal gravitation had a similar impact, starting a revolution in celestial mechanics and astronomy that continues to this day. With the advent of this theory, the orbits of all the planets could be calculated to high precision and the tides understood. The theory even led to the prediction of “dark stars,” now called black holes, more than two centuries before any evidence for their existence was observed.

Newton’s three laws of motion, together with his law of gravitation, are considered among the greatest achievements of the human mind.

4.1 FORCES

A force is commonly imagined as a push or a pull on some object, perhaps rapidly, as when we hit a tennis ball with a racket. (See Fig. 4.1.) We can hit the ball at different speeds and direct it into different parts of the opponent’s court. This means that we can control the magnitude of the applied force and also its direction, so force is a vector quantity, just like velocity and acceleration.

1In 1783, John Michell combined Newton’s theory of light and theory of gravitation, predicting the existence of “dark stars” from which light itself couldn’t escape.

FIGURE 4.1 Tennis champion Rafael Nadal strikes the ball with his racket, applying a force and directing the ball into the open part of the court.
If you pull on a spring (Fig. 4.2a), the spring stretches. If you pull hard enough on a wagon (Fig. 4.2b), the wagon moves. When you kick a football (Fig. 4.2c), it deforms briefly and is set in motion. These are all examples of **contact forces**, so named because they result from physical contact between two objects.

Another class of forces doesn’t involve any direct physical contact. Early scientists, including Newton, were uneasy with the concept of forces that act between two disconnected objects. Nonetheless, Newton used this “action-at-a-distance” concept in his law of gravity, whereby a mass at one location, such as the Sun, affects the motion of a distant object such as Earth despite no evident physical connection between the two objects. To overcome the conceptual difficulty associated with action at a distance, Michael Faraday (1791–1867) introduced the concept of a **field**. The corresponding forces are called **field forces**. According to this approach, an object of mass \( M \), such as the Sun, creates an invisible influence that stretches throughout space. A second object of mass \( m \), such as Earth, interacts with the field of the Sun, not directly with the Sun itself. So the force of gravitational attraction between two objects, illustrated in Figure 4.2d, is an example of a field force. The force of gravity keeps objects bound to Earth and also gives rise to what we call the **weight** of those objects.

Another common example of a field force is the electric force that one electric charge exerts on another (Fig. 4.2e). A third example is the force exerted by a bar magnet on a piece of iron (Fig. 4.2f).

The known fundamental forces in nature are all field forces. These are, in order of decreasing strength, (1) the strong nuclear force between subatomic particles, (2) the electromagnetic forces between electric charges, (3) the weak nuclear force, which arises in certain radioactive decay processes, and (4) the gravitational force between objects. The strong force keeps the nucleus of an atom from flying apart due to the repulsive electric force of the protons. The weak force is involved in most radioactive processes and plays an important role in the nuclear reactions that generate the Sun’s energy output. The strong and weak forces operate only on the nuclear scale, with a very short range on the order of \( 10^{-15} \) m. Outside this range, they have no influence. Classical physics, however, deals only with gravitational and electromagnetic forces, which have infinite range.

Forces exerted on an object can change the object’s shape. For example, striking a tennis ball with a racket, as in Figure 4.1, deforms the ball to some extent. Even objects we usually consider rigid and inflexible are deformed under the action of external forces. Often the deformations are permanent, as in the case of a collision between automobiles.
4.2 Newton’s First Law

Consider a book lying on a table. Obviously, the book remains at rest if left alone. Now imagine pushing the book with a horizontal force great enough to overcome the force of friction between the book and the table, setting the book in motion. Because the magnitude of the applied force exceeds the magnitude of the friction force, the book accelerates. When the applied force is withdrawn, friction soon slows the book to a stop.

Now imagine pushing the book across a smooth, waxed floor. The book again comes to rest once the force is no longer applied, but not as quickly as before. Finally, if the book is moving on a horizontal frictionless surface, it continues to move in a straight line with constant velocity until it hits a wall or some other obstruction.

Before about 1600, scientists felt that the natural state of matter was the state of rest. Galileo, however, devised thought experiments—such as an object moving on a frictionless surface, as just described—and concluded that it’s not the nature of an object to stop, once set in motion, but rather to continue in its original state of motion. This approach was later formalized as Newton’s first law of motion:

An object moves with a velocity that is constant in magnitude and direction, unless acted on by a nonzero net force.

The net force on an object is defined as the vector sum of all external forces exerted on the object. External forces come from the object’s environment. If an object’s velocity isn’t changing in either magnitude or direction, then its acceleration and the net force acting on it must both be zero.

Internal forces originate within the object itself and can’t change the object’s velocity (although they can change the object’s rate of rotation, as described in Chapter 8). As a result, internal forces aren’t included in Newton’s second law. It’s not really possible to “pull yourself up by your own bootstraps.”

A consequence of the first law is the feasibility of space travel. After just a few moments of powerful thrust, the spacecraft coasts for months or years, its velocity only slowly changing with time under the relatively faint influence of the distant sun and planets.

Mass and Inertia

Imagine hitting a golf ball off a tee with a driver. If you’re a good golfer, the ball will sail over two hundred yards down the fairway. Now imagine teeing up a bowling ball and striking it with the same club (an experiment we don’t recommend). Your club would probably break, you might sprain your wrist, and the bowling ball, at best, would fall off the tee, take half a roll, and come to rest.

From this thought experiment, we conclude that although both balls resist changes in their state of motion, the bowling ball offers much more effective resistance. The tendency of an object to continue in its original state of motion is called inertia.

Although inertia is the tendency of an object to continue its motion in the absence of a force, mass is a measure of the object’s resistance to changes in its motion due to a force. The greater the mass of a body, the less it accelerates under the action of a given applied force. The SI unit of mass is the kilogram. Mass is a scalar quantity that obeys the rules of ordinary arithmetic.

Inertia can be used to explain the operation of one type of seat belt mechanism. In the event of an accident, the purpose of the seat belt is to hold the passenger firmly in place relative to the car, to prevent serious injury. Figure 4.3 (page 86) illustrates how one type of shoulder harness operates. Under normal conditions, the ratchet turns freely to allow the harness to wind on or unwind from the pulley as the passenger moves. In an accident, the car undergoes a large acceleration and inertia moves the passenger forward. Unless acted on by an external force, an object at rest will remain at rest and an object in motion will continue in motion with constant velocity. In this case, the wall of the building did not exert a large enough external force on the moving train to stop it.
rapidly comes to rest. Because of its inertia, the large block under the seat continues to slide forward along the tracks. The pin connection between the block and the rod causes the rod to pivot about its center and engage the ratchet wheel. At this point, the ratchet wheel locks in place and the harness no longer unwinds.

4.3 NEWTON’S SECOND LAW

Newton’s first law explains what happens to an object that has no net force acting on it: The object either remains at rest or continues moving in a straight line with constant speed. Newton’s second law answers the question of what happens to an object that does have a net force acting on it.

Imagine pushing a block of ice across a frictionless horizontal surface. When you exert some horizontal force on the block, it moves with an acceleration of, say, 2 m/s$^2$. If you apply a force twice as large, the acceleration doubles to 4 m/s$^2$. Pushing three times as hard triples the acceleration, and so on. From such observations, we conclude that the acceleration of an object is directly proportional to the net force acting on it.

Mass also affects acceleration. Suppose you stack identical blocks of ice on top of each other while pushing the stack with constant force. If the force applied to one block produces an acceleration of 2 m/s$^2$, then the acceleration drops to half that value, 1 m/s$^2$, when two blocks are pushed, to one-third the initial value when three blocks are pushed, and so on. We conclude that the acceleration of an object is inversely proportional to its mass. These observations are summarized in Newton’s second law:

**Newton’s second law**

The acceleration \( \vec{a} \) of an object is directly proportional to the net force acting on it and inversely proportional to its mass.

The constant of proportionality is equal to one, so in mathematical terms the preceding statement can be written

\[
\vec{a} = \frac{\sum \vec{F}}{m}
\]

where \( \vec{a} \) is the acceleration of the object, \( m \) is its mass, and \( \sum \vec{F} \) is the vector sum of all forces acting on it. Multiplying through by \( m \), we have

\[
\sum \vec{F} = ma \quad [4.1]
\]
Physicists commonly refer to this equation as ‘\( F = ma \)’. The second law is a vector equation, equivalent to the following three component equations:

\[
\sum F_x = ma_x, \quad \sum F_y = ma_y, \quad \sum F_z = ma_z
\] [4.2]

When there is no net force on an object, its acceleration is zero, which means the velocity is constant.

### Units of Force and Mass

The SI unit of force is the **newton**. When 1 newton of force acts on an object that has a mass of 1 kg, it produces an acceleration of 1 m/s\(^2\) in the object. From this definition and Newton’s second law, we see that the newton can be expressed in terms of the fundamental units of mass, length, and time as

\[
1 \text{ N} = 1 \text{ kg} \cdot \text{m/s}^2
\] [4.3]

In the U.S. customary system, the unit of force is the **pound**. The conversion from newtons to pounds is given by

\[
1 \text{ N} = 0.225 \text{ lb}
\] [4.4]

The units of mass, acceleration, and force in the SI and U.S. customary systems are summarized in Table 4.1.

<table>
<thead>
<tr>
<th>TABLE 4.1</th>
<th>Units of Mass, Acceleration, and Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>System</td>
<td>Mass</td>
</tr>
<tr>
<td>SI</td>
<td>kg</td>
</tr>
<tr>
<td>U.S. customary</td>
<td>slug</td>
</tr>
</tbody>
</table>

### QUICK QUIZ 4.1

Which of the following statements are true? (a) An object can move even when no force acts on it. (b) If an object isn’t moving, no external forces act on it. (c) If a single force acts on an object, the object accelerates. (d) If an object accelerates, a force is acting on it. (e) If an object isn’t accelerating, no external force is acting on it. (f) If the net force acting on an object is in the positive \( x \)-direction, the object moves only in the positive \( x \)-direction.

### EXAMPLE 4.1 Airboat

**Goal** Apply Newton’s law in one dimension, together with the equations of kinematics.

**Problem** An airboat with mass \( 3.50 \times 10^2 \) kg, including passengers, has an engine that produces a net horizontal force of \( 7.70 \times 10^2 \) N, after accounting for forces of resistance (see Fig. 4.4). (a) Find the acceleration of the airboat. (b) Starting from rest, how long does it take the airboat to reach a speed of 12.0 m/s? (c) After reaching this speed, the pilot turns off the engine and drifts to a stop over a distance of 50.0 m. Find the resistance force, assuming it’s constant.

**Strategy** In part (a), apply Newton’s second law to find the acceleration, and in part (b) use this acceleration in the one-dimensional kinematics equation for the velocity. When the engine is turned off in part (c), only the resistance forces act on the boat, so their net acceleration can be found from \( v_f^2 - v_i^2 = 2a \Delta x \). Then Newton’s second law gives the resistance force.
Solution
(a) Find the acceleration of the airboat.

Apply Newton’s second law and solve for the acceleration:

\[ ma = F_{\text{net}} \rightarrow a = \frac{F_{\text{net}}}{m} = \frac{7.70 \times 10^3 \text{ N}}{3.50 \times 10^2 \text{ kg}} = 2.20 \text{ m/s}^2 \]

(b) Find the time necessary to reach a speed of 12.0 m/s.

Apply the kinematics velocity equation:

\[ v = at + v_0 = (2.20 \text{ m/s})t + 12.0 \text{ m/s} \rightarrow t = 5.45 \text{ s} \]

(c) Find the resistance force after the engine is turned off.

Using kinematics, find the net acceleration due to resistance forces:

\[ v^2 - v_0^2 = 2a \Delta x \]
\[ 0 - (12.0 \text{ m/s})^2 = 2a(50.0 \text{ m}) \rightarrow a = -1.44 \text{ m/s}^2 \]

Substitute the acceleration into Newton’s second law, finding the resistance force:

\[ F_{\text{resist}} = ma = (3.50 \times 10^2 \text{ kg})(-1.44 \text{ m/s}^2) = -504 \text{ N} \]

Remarks    The propeller exerts a force on the air, pushing it backwards behind the boat. At the same time, the air exerts a force on the propellers and consequently on the airboat. Forces always come in pairs of this kind, which are formalized in the next section as Newton’s third law of motion. The negative answer for the acceleration in part (c) means that the airboat is slowing down.

QUESTION 4.1
What other forces act on the airboat? Describe them.

EXERCISE 4.1
Suppose the pilot, starting again from rest, opens the throttle partway. At a constant acceleration, the airboat then covers a distance of 60.0 m in 10.0 s. Find the net force acting on the boat.

Answer    \( 4.20 \times 10^2 \text{ N} \)

EXAMPLE 4.2    Horses Pulling a Barge

Goal    Apply Newton’s second law in a two-dimensional problem.

Problem    Two horses are pulling a barge with mass \( 2.00 \times 10^3 \text{ kg} \) along a canal, as shown in Figure 4.5. The cable connected to the first horse makes an angle of 30.0° with respect to the direction of the canal, while the cable connected to the second horse makes an angle of 45.0°. Find the initial acceleration of the barge, starting at rest, if each horse exerts a force of magnitude \( 6.00 \times 10^2 \text{ N} \) on the barge. Ignore forces of resistance on the barge.

Strategy    Using trigonometry, find the vector force exerted by each horse on the barge. Add the \( x \)-components together to get the \( x \)-component of the resultant force, and then do the same with the \( y \)-components. Divide by the mass of the barge to get the accelerations in the \( x \)- and \( y \)-directions.
The Gravitational Force

The gravitational force is the mutual force of attraction between any two objects in the Universe. Although the gravitational force can be very strong between very large objects, it's the weakest of the fundamental forces. A good demonstration of how weak it is can be carried out with a small balloon. Rubbing the balloon in your hair gives the balloon a tiny electric charge. Through electric forces, the balloon then adheres to a wall, resisting the gravitational pull of the entire Earth!
In addition to contributing to the understanding of motion, Newton studied gravity extensively. **Newton’s law of universal gravitation** states that every particle in the Universe attracts every other particle with a force that is directly proportional to the product of the masses of the particles and inversely proportional to the square of the distance between them. If the particles have masses \( m_1 \) and \( m_2 \) and are separated by a distance \( r \), as in Active Figure 4.6, the magnitude of the gravitational force, \( F_g \), is

\[
F_g = G \frac{m_1 m_2}{r^2}
\]

where \( G = 6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2 \) is the **universal gravitation constant**. We examine the gravitational force in more detail in Chapter 7.

**Weight**

The magnitude of the gravitational force acting on an object of mass \( m \) near Earth’s surface is called the **weight**, \( w \), of the object, given by

\[
w = mg
\]

where \( g \) is the acceleration of gravity.

**SI unit: newton (N)**

From Equation 4.5, an alternate definition of the weight of an object with mass \( m \) can be written as

\[
w = G \frac{M_E m}{r^2}
\]

where \( M_E \) is the mass of Earth and \( r \) is the distance from the object to Earth’s center. If the object is at rest on Earth’s surface, then \( r \) is equal to Earth’s radius \( R_E \).

Since \( r \) is in the denominator of Equation 4.7, the weight decreases with increasing \( r \). So the weight of an object on a mountaintop is less than the weight of the same object at sea level.

Comparing Equations 4.6 and 4.7, we see that

\[
g = G \frac{M_E}{r^2}
\]

Unlike mass, weight is not an inherent property of an object because it can take different values, depending on the value of \( g \) in a given location. If an object has a mass of 70.0 kg, for example, then its weight at a location where \( g = 9.80 \text{ m/s}^2 \) is \( mg = 686 \text{ N} \). In a high-altitude balloon, where \( g \) might be 9.76 m/s\(^2\), the object’s weight would be 683 N. The value of \( g \) also varies slightly due to the density of matter in a given locality.

Equation 4.8 is a general result that can be used to calculate the acceleration of an object falling near the surface of any massive object if the more massive object’s radius and mass are known. Using the values in Table 7.3 (p. 217), you should be able to show that \( g_{\text{Sun}} = 274 \text{ m/s}^2 \) and \( g_{\text{Moon}} = 1.62 \text{ m/s}^2 \). An important fact is that for spherical bodies, distances are calculated from the centers of the objects, a consequence of Gauss’s law (explained in Chapter 15), which holds for both gravitational and electric forces.

**QUICK QUIZ 4.2** Which has greater value, a newton of gold won on Earth or a newton of gold won on the Moon? (a) The newton of gold on the Earth. (b) The newton of gold on the Moon. (c) The value is the same, regardless.
EXAMPLE 4.3  Forces of Distant Worlds

Goal Calculate the magnitude of a gravitational force using Newton’s law of gravitation.

Problem Find the gravitational force exerted by the Sun on a 70.0-kg man located on Earth. The distance from the Sun to the Earth is about $1.50 \times 10^{11}$ m, and the Sun’s mass is $1.99 \times 10^{30}$ kg.

Strategy Substitute numbers into Newton’s law of gravitation, Equation 4.5, making sure to use the correct units.

Solution Apply Equation 4.5, substituting values:

$$F_{\text{Sun}} = G \frac{m M}{r^2}$$

$$= (6.67 \times 10^{-11} \text{ kg}^{-1} \text{m}^3 \text{s}^{-2}) \frac{(70.0 \text{ kg})(1.99 \times 10^{30} \text{ kg})}{(1.50 \times 10^{11} \text{ m})^2}$$

$$= 0.413 \text{ N}$$

Remarks The gravitational attraction between the Sun and objects on Earth is easily measurable and has been exploited in experiments to determine whether gravitational attraction depends on the composition of the object. As the exercise shows, the gravitational force on Earth due to the Moon is much weaker than the gravitational force on Earth due to the Sun. Paradoxically, the Moon’s effect on the tides is over twice that of the Sun because the tides depend on differences in the gravitational force across the Earth, and those differences are greater for the Moon’s gravitational force because the Moon is much closer to Earth than the Sun.

QUESTION 4.3

Mars is about one and a half times as far from the Sun as Earth. To one significant digit, what is the gravitational force of the Sun on a 70.0 kg man standing on Mars? (Hint: Use the result of part (a) and the inverse square nature of the force.)

EXERCISE 4.3

To one significant digit, find the force exerted by the Moon on a 70-kg man on Earth. The Moon has a mass of $7.36 \times 10^{22}$ kg and is $3.84 \times 10^8$ m from Earth.

Answer $F_{\text{Moon}} = 0.002 \text{ N}$

EXAMPLE 4.4  Weight on Planet X

Goal Understand the effect of a planet’s mass and radius on the weight of an object on the planet’s surface.

Problem An astronaut on a space mission lands on a planet with three times the mass and twice the radius of Earth. What is her weight $w_X$ on this planet as a multiple of her Earth weight $w_E$?

Strategy Write $M_X$ and $r_X$, the mass and radius of the planet, in terms of $M_E$ and $R_E$, the mass and radius of Earth, respectively, and substitute into the law of gravitation.

Solution From the statement of the problem, we have the following relationships:

$M_X = 3M_E$ \hspace{1cm} $r_X = 2R_E$

Substitute the preceding expressions into Equation 4.5 and simplify, algebraically associating the terms giving the weight on Earth:

$$w_X = G \frac{M_X m}{r_X^2} = G \frac{3M_E m}{(2R_E)^2} = \frac{3}{4} \frac{M_E m}{R_E^2} = \frac{3}{4} w_E$$

Remarks This problem shows the interplay between a planet’s mass and radius in determining the weight of objects on its surface. Because of Earth’s much smaller radius, the weight of an object on Jupiter is only 2.64 times its weight on Earth, despite the fact that Jupiter has over 300 times as much mass.
QUESTION 4.4
Suppose one world is made of ice whereas another world with the same radius is made of rock. If \( g \) is the acceleration of gravity on the surface of the ice world, what is the approximate acceleration of gravity on the rock world? (Hint: Estimate the mass of a rock in terms of the mass of an ice cube having the same size.)

EXERCISE 4.4
An astronaut lands on Ganymede, a giant moon of Jupiter that is larger than the planet Mercury. Ganymede has one-fortieth the mass of Earth and two-fifths the radius. Find the weight of the astronaut standing on Ganymede in terms of his Earth weight \( w_E \).

**Answer** \( w_G = (5/32)w_E \)

### 4.4 NEWTON’S THIRD LAW

In Section 4.1 we found that a force is exerted on an object when it comes into contact with some other object. Consider the task of driving a nail into a block of wood, for example, as illustrated in Figure 4.7a. To accelerate the nail and drive it into the block, the hammer must exert a net force on the nail. Newton recognized, however, that a single isolated force (such as the force exerted by the hammer on the nail) couldn’t exist. Instead, **forces in nature always exist in pairs.** According to Newton, as the nail is driven into the block by the force exerted by the hammer, the hammer is slowed down and stopped by the force exerted by the nail.

Newton described such paired forces with his **third law**:

If object 1 and object 2 interact, the force \( F_{12} \) exerted by object 1 on object 2 is equal in magnitude but opposite in direction to the force \( F_{21} \) exerted by object 2 on object 1.

This law, which is illustrated in Figure 4.7b, states that a **single isolated force can’t exist**. The force \( F_{12} \) exerted by object 1 on object 2 is sometimes called the **action force**, and the force \( F_{21} \) exerted by object 2 on object 1 is called the **reaction force**. In reality, either force can be labeled the action or reaction force. The action force is equal in magnitude to the reaction force and opposite in direction. In all cases, the action and reaction forces act on different objects. For example, the force acting on a freely falling projectile is the force exerted by Earth on the projectile, \( F_E \), and the magnitude of this force is its weight \( mg \). The reaction to force \( F_E \) is the force exerted by the projectile on Earth, \( F_E' = -F_E \). The reaction force \( F_E' \) must accelerate the Earth towards the projectile, just as the action force \( F_E \) accelerates the projectile towards the Earth. Because the...
Earth has such a large mass, however, its acceleration due to this reaction force is negligibly small.

Newton’s third law constantly affects our activities in everyday life. Without it, no locomotion of any kind would be possible, whether on foot, on a bicycle, or in a motorized vehicle. When walking, for example, we exert a frictional force against the ground. The reaction force of the ground against our foot propels us forward. In the same way, the tires on a bicycle exert a frictional force against the ground, and the reaction of the ground pushes the bicycle forward. As we’ll see shortly, friction plays a large role in such reaction forces.

For another example of Newton’s third law, consider the helicopter. Most helicopters have a large set of blades rotating in a horizontal plane above the body of the vehicle and another, smaller set rotating in a vertical plane at the back. Other helicopters have two large sets of blades above the body rotating in opposite directions. Why do helicopters always have two sets of blades? In the first type of helicopter, the engine applies a force to the blades, causing them to change their rotational motion. According to Newton’s third law, however, the blades must exert a force on the engine of equal magnitude and in the opposite direction. This force would cause the body of the helicopter to rotate in the direction opposite the blades. A rotating helicopter would be impossible to control, so a second set of blades is used. The small blades in the back provide a force opposite to that tending to rotate the body of the helicopter, keeping the body oriented in a stable position. In helicopters with two sets of large counterrotating blades, engines apply forces in opposite directions, so there is no net force rotating the helicopter.

As mentioned earlier, the Earth exerts a force \( \vec{F}_g \) on any object. If the object is a TV at rest on a table, as in Figure 4.8a, the reaction force to \( \vec{F}_g \) is the force the TV exerts on the Earth, \( \vec{F}_g' \). The TV doesn’t accelerate downward because it’s held up by the table. The table therefore exerts an upward force \( \vec{n} \), called the normal force, on the TV. (Normal, a technical term from mathematics, means “perpendicular” in this context.) The normal force is an elastic force arising from the cohesion of matter and is electromagnetic in origin. It balances the gravitational force acting on the TV, preventing the TV from falling through the table, and can have any value needed, up to the point of breaking the table. The reaction to \( \vec{n} \) is the force exerted by the TV on the table, \( \vec{n}' \). Therefore,

\[
\vec{F}_g = -\vec{F}_g' \quad \text{and} \quad \vec{n} = -\vec{n}'
\]

The forces \( \vec{n} \) and \( \vec{n}' \) both have the same magnitude as \( \vec{F}_g \). Note that the forces acting on the TV are \( \vec{F}_g \) and \( \vec{n} \), as shown in Figure 4.8b. The two reaction forces, \( \vec{F}_g' \) and \( \vec{n}' \), are exerted by the TV on objects other than the TV. Remember that the two forces in an action–reaction pair always act on two different objects.

**APPLICATION**

*Helicopter Flight*

**FIGURE 4.8** When a TV set is sitting on a table, the forces acting on the set are the normal force \( \vec{n} \) exerted by the table and the force of gravity, \( \vec{F}_g \), as illustrated in (b). The reaction to \( \vec{n} \) is the force exerted by the TV set on the table, \( \vec{n}' \). The reaction to \( \vec{F}_g \) is the force exerted by the TV set on Earth, \( \vec{F}_g' \).
Because the TV is not accelerating in any direction ($\vec{a} = 0$), it follows from Newton’s second law that $m\vec{a} = 0 = \vec{F}_e + \vec{n}$. However, $\vec{F}_e = -mg$, so $n = mg$, a useful result.

**QUICK QUIZ 4.3** A small sports car collides head-on with a massive truck. The greater impact force (in magnitude) acts on (a) the car, (b) the truck, (c) neither, the force is the same on both. Which vehicle undergoes the greater magnitude acceleration? (d) the car, (e) the truck, (f) the accelerations are the same.

### 4.5 APPLICATIONS OF NEWTON’S LAWS

This section applies Newton’s laws to objects moving under the influence of constant external forces. We assume that objects behave as particles, so we need not consider the possibility of rotational motion. We also neglect any friction effects and the masses of any ropes or strings involved. With these approximations, the magnitude of the force exerted along a rope, called the **tension**, is the same at all points in the rope. This is illustrated by the rope in Figure 4.9, showing the forces $\vec{T}$ and $\vec{T}'$ acting on it. If the rope has mass $m$, then Newton’s second law applied to the rope gives $T - T' = ma$. If the mass $m$ is taken to be negligible, however, as in the upcoming examples, then $T = T'$.

When we apply Newton’s law to an object, we are interested only in those forces which act on the object. For example, in Figure 4.8b, the only external forces acting on the TV are $\vec{n}$ and $\vec{F}_g$. The reactions to these forces, $\vec{n}'$ and $\vec{F}_g'$, act on the table and on Earth, respectively, and don’t appear in Newton’s second law applied to the TV.

Consider a crate being pulled to the right on a frictionless, horizontal surface, as in Figure 4.10a. Suppose you wish to find the acceleration of the crate and the force the surface exerts on it. The horizontal force exerted on the crate acts through the rope. The force that the rope exerts on the crate is denoted by $\vec{T}$ (because it’s a tension force). The magnitude of $\vec{T}$ is equal to the tension in the rope. What we mean by the words “tension in the rope” is just the force read by a spring scale when the rope in question has been cut and the scale inserted between the cut ends. A dashed circle is drawn around the crate in Figure 4.10a to emphasize the importance of isolating the crate from its surroundings.

**Because we are interested only in the motion of the crate, we must be able to identify all forces acting on it.** These forces are illustrated in Figure 4.10b. In addition to displaying the force $\vec{T}$, the force diagram for the crate includes the force of gravity $\vec{F}_g$ exerted by Earth and the normal force $\vec{n}$ exerted by the floor. Such a force diagram is called a **free-body diagram** because the environment is replaced by a series of forces on an otherwise free body. The construction of a correct free-body diagram is an essential step in applying Newton’s laws. An incorrect diagram will most likely lead to incorrect answers!

The **reactions** to the forces we have listed—namely, the force exerted by the rope on the hand doing the pulling, the force exerted by the crate on Earth, and the force exerted by the crate on the floor—aren’t included in the free-body diagram because they act on other objects and not on the crate. Consequently, they don’t directly influence the crate’s motion. Only forces acting directly on the crate are included.

Now let’s apply Newton’s second law to the crate. First we choose an appropriate coordinate system. In this case it’s convenient to use the one shown in Figure 4.10b, with the $x$-axis horizontal and the $y$-axis vertical. We can apply Newton’s second law in the $x$-direction, $y$-direction, or both, depending on what we’re asked.
to find in a problem. Newton’s second law applied to the crate in the \( x \)- and \( y \)-
directions yields the following two equations:

\[
ma_x = T \\
ma_y = n - mg = 0
\]

From these equations, we find that the acceleration in the \( x \)-direction is constant, given by \( a_x = T/m \), and that the normal force is given by \( n = mg \). Because the acceleration is constant, the equations of kinematics can be applied to obtain further information about the velocity and displacement of the object.

**PROBLEM-SOLVING STRATEGY**

**NEWTON’S SECOND LAW**

Problems involving Newton’s second law can be very complex. The following
protocol breaks the solution process down into smaller, intermediate goals:

1. Read the problem carefully at least once.
2. Draw a picture of the system, identify the object of primary interest, and indicate forces with arrows.
3. Label each force in the picture in a way that will bring to mind what physical quantity the label stands for (e.g., \( T \) for tension).
4. Draw a free-body diagram of the object of interest, based on the labeled picture. If additional objects are involved, draw separate free-body diagrams for them. Choose convenient coordinates for each object.
5. Apply Newton’s second law. The \( x \)- and \( y \)-components of Newton’s second
law should be taken from the vector equation and written individually. This usually results in two equations and two unknowns.
6. Solve for the desired unknown quantity, and substitute the numbers.

In the special case of equilibrium, the foregoing process is simplified because the
acceleration is zero.

**Objects in Equilibrium**

Objects that are either at rest or moving with constant velocity are said to be in equilibrium. Because \( \vec{a} = 0 \), Newton’s second law applied to an object in equilibrium gives

\[
\sum \vec{F} = 0
\]

This statement signifies that the \textit{vector} sum of all the forces (the net force) acting on an object in equilibrium is zero. Equation 4.9 is equivalent to the set of component equations given by

\[
\sum F_x = 0 \quad \text{and} \quad \sum F_y = 0
\]

We won’t consider three-dimensional problems in this book, but the extension of Equation 4.10 to a three-dimensional problem can be made by adding a third equation: \( \Sigma F_z = 0 \).

**QUICK QUIZ 4.4** Consider the two situations shown in Figure 4.11, in which there is no acceleration. In both cases the men pull with a force of magnitude \( F \). Is the reading on the scale in part (i) of the figure (a) greater than, (b) less than, or (c) equal to the reading in part (ii)?

**TIP 4.6 A Particle in Equilibrium**

A zero net force on a particle does \textit{not} mean that the particle isn’t moving. It means that the particle isn’t \textit{accelerating}. If the particle has a nonzero initial velocity and is acted upon by a zero net force, it continues to move with the same velocity.
EXAMPLE 4.5  A Traffic Light at Rest

Goal  Use the second law in an equilibrium problem requiring two free-body diagrams.

Problem A traffic light weighing \(1.00 \times 10^2\) N hangs from a vertical cable tied to two other cables that are fastened to a support, as in Figure 4.12a. The upper cables make angles of 37.0° and 53.0° with the horizontal. Find the tension in each of the three cables.

Strategy  There are three unknowns, so we need to generate three equations relating them, which can then be solved. One equation can be obtained by applying Newton’s second law to the traffic light, which has forces in the y-direction only. Two more equations can be obtained by applying the second law to the knot joining the cables—one equation from the x-component and one equation from the y-component.

Solution  Find \(T_3\) from Figure 4.12b, using the condition of equilibrium:

\[
\sum F_y = 0 \quad \Rightarrow \quad T_3 - F_g = 0
\]

\[
T_3 = F_g = 1.00 \times 10^2 \text{ N}
\]

Using Figure 4.12c, resolve all three tension forces into components and construct a table for convenience:

<table>
<thead>
<tr>
<th>Force</th>
<th>x-Component</th>
<th>y-Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T_1)</td>
<td>(-T_1 \cos 37.0°)</td>
<td>(T_1 \sin 37.0°)</td>
</tr>
<tr>
<td>(T_2)</td>
<td>(T_2 \cos 53.0°)</td>
<td>(T_2 \sin 53.0°)</td>
</tr>
<tr>
<td>(T_3)</td>
<td>0</td>
<td>(-1.00 \times 10^2 \text{ N})</td>
</tr>
</tbody>
</table>

Apply the conditions for equilibrium to the knot, using the components in the table:

(1) \[ \sum F_y = -T_1 \cos 37.0° + T_2 \cos 53.0° = 0 \]

(2) \[ \sum F_x = T_1 \sin 37.0° + T_2 \sin 53.0° - 1.00 \times 10^2 \text{ N} = 0 \]

There are two equations and two remaining unknowns. Solve Equation (1) for \(T_2\):

\[ T_2 = T_1 \left( \frac{\cos 37.0°}{\cos 53.0°} \right) = T_1 \left( \frac{0.799}{0.602} \right) = 1.33T_1 \]

Substitute the result for \(T_2\) into Equation (2):

\[ T_1 \sin 37.0° + (1.33T_1)(\sin 53.0°) - 1.00 \times 10^2 \text{ N} = 0 \]

\[ T_1 = 60.1 \text{ N} \]

\[ T_2 = 1.33T_1 = 1.33(60.0 \text{ N}) = 79.9 \text{ N} \]

Remarks  It’s very easy to make sign errors in this kind of problem. One way to avoid them is to always measure the angle of a vector from the positive x-direction. The trigonometric functions of the angle will then automatically give the correct signs for the components. For example, \(T_1\) makes an angle of \(180° - 37° = 143°\) with respect to the positive x-axis, and its x-component, \(T_1 \cos 143°\), is negative, as it should be.

QUESTION 4.5  How would the answers change if a second traffic light were attached beneath the first?

EXERCISE 4.5  Suppose the traffic light is hung so that the tensions \(T_3\) and \(T_4\) are both equal to 80.0 N. Find the new angles they make with respect to the x-axis. (By symmetry, these angles will be the same.)

Answer  Both angles are 38.7°.
**EXAMPLE 4.6 Sled on a Frictionless Hill**

**Goal** Use the second law and the normal force in an equilibrium problem.

**Problem** A sled is tied to a tree on a frictionless, snow-covered hill, as shown in Figure 4.13a. If the sled weighs 77.0 N, find the force exerted by the rope on the sled and the magnitude of the force $\mathbf{n}$ exerted by the hill on the sled.

**Strategy** When an object is on a slope, it's convenient to use tilted coordinates, as in Figure 4.13b, so that the normal force $\mathbf{n}$ is in the $y$-direction and the tension force $\mathbf{T}$ is in the $x$-direction. In the absence of friction, the hill exerts no force on the sled in the $x$-direction. Because the sled is at rest, the conditions for equilibrium, $\Sigma F_x = 0$ and $\Sigma F_y = 0$, apply, giving two equations for the two unknowns—the tension and the normal force.

**Solution** Apply Newton’s second law to the sled, with $\mathbf{a} = 0$: 

$$\sum \mathbf{F} = \mathbf{T} + \mathbf{n} + \mathbf{F}_g = 0$$

Extract the $x$-component from this equation to find $T$. The $x$-component of the normal force is zero, and the sled’s weight is given by $mg = 77.0$ N.

$$T = 0 - mg \sin \theta = T - (77.0 \text{ N}) \sin 30.0^\circ = 0$$

$$T = 38.5 \text{ N}$$

Write the $y$-component of Newton’s second law. The $y$-component of the tension is zero, so this equation will give the normal force.

$$\sum F_y = 0 + n - mg \cos \theta = n - (77.0 \text{ N})(\cos 30.0^\circ) = 0$$

$$n = 66.7 \text{ N}$$

**Remarks** Unlike its value on a horizontal surface, $n$ is less than the weight of the sled when the sled is on the slope. This is because only part of the force of gravity (the $x$-component) is acting to pull the sled down the slope. The $y$-component of the force of gravity balances the normal force.

**QUESTION 4.6**
Consider the same scenario on a hill with a steeper slope. Would the magnitude of the tension in the rope get larger, smaller, or remain the same as before? How would the normal force be affected?

**EXERCISE 4.6**
Suppose a child of weight $w$ climbs onto the sled. If the tension force is measured to be 60.0 N, find the weight of the child and the magnitude of the normal force acting on the sled.

**Answers** $w = 43.0 \text{ N}$, $n = 104 \text{ N}$

**QUICK QUIZ 4.5** For the woman being pulled forward on the toboggan in Figure 4.14, is the magnitude of the normal force exerted by the ground on the toboggan (a) equal to the total weight of the woman plus the toboggan, (b) greater than the total weight, (c) less than the total weight, or (d) possibly greater than or less than the total weight, depending on the size of the weight relative to the tension in the rope?

**Accl erating Objects and Newton’s Second Law**
When a net force acts on an object, the object accelerates, and we use Newton’s second law to analyze the motion.

**FIGURE 4.14** (Quick Quiz 4.5)
EXAMPLE 4.7  Moving a Crate

Goal  Apply the second law of motion for a system not in equilibrium, together with a
kinematics equation.

Problem  The combined weight of the crate and dolly in Figure 4.15 is $3.00 \times 10^2$ N. If
the man pulls on the rope with a constant force of 20.0 N, what is the acceleration of the
system (crate plus dolly), and how far will it move in 2.00 s? Assume the system starts from
rest and that there are no friction forces opposing the motion.

Strategy  We can find the acceleration of the system from Newton’s second law. Because
the force exerted on the system is constant, its acceleration is constant. Therefore, we can
apply a kinematics equation to find the distance traveled in 2.00 s.

Solution

Find the mass of the system from the definition of weight, $w = mg$:

$$m = \frac{w}{g} = \frac{3.00 \times 10^2 \text{ N}}{9.80 \text{ m/s}^2} = 30.6 \text{ kg}$$

Find the acceleration of the system from the second law:

$$a = \frac{F}{m} = \frac{20.0 \text{ N}}{30.6 \text{ kg}} = 0.654 \text{ m/s}^2$$

Use kinematics to find the distance moved in 2.00 s, $\Delta x = \frac{1}{2} a t^2 = \frac{1}{2} \cdot (0.654 \text{ m/s}^2)(2.00 \text{ s})^2 = 1.31 \text{ m}$

Remarks  Note that the constant applied force of 20.0 N is assumed to act on the system at all times during its
motion. If the force were removed at some instant, the system would continue to move with constant velocity and
hence zero acceleration. The rollers have an effect that was neglected, here.

QUESTION 4.7

What effect does doubling the weight have on the acceleration and the displacement?

EXERCISE 4.7

A man pulls a 50.0-kg box horizontally from rest while exerting a constant horizontal force, displacing the box
3.00 m in 2.00 s. Find the force the man exerts on the box. (Ignore friction.)

Answer  75.0 N

EXAMPLE 4.8  The Runaway Car

Goal  Apply the second law and kinematic equations to a problem involving an object moving on an incline.

Problem  (a) A car of mass $m$ is on an icy driveway inclined at an angle $\theta = 20.0^\circ$, as in Figure 4.16a.
Determine the acceleration of the car, assuming the incline is frictionless. (b) If the length of
the driveway is 25.0 m and the car starts from rest at the top, how long does it take to travel to the bot-
tom? (c) What is the car’s speed at the bottom?

Strategy  Choose tilted coordinates as in Figure 4.16b so that the normal force $\mathbf{n}$ is in the positive
$y$-direction, perpendicular to the driveway, and the positive $x$-axis is down the slope. The
force of gravity $\mathbf{F}_g$ then has an $x$-component, $mg \sin \theta$, and a $y$-component, $-mg \cos \theta$. The com-
ponents of Newton’s second law form a system of two equations and two unknowns for the ac-
celeration down the slope, $a_x$, and the normal force. Parts (b) and (c) can be solved with the kinematics equations.
Solution
(a) Find the acceleration of the car.

Apply Newton’s second law:
\[ m \ddot{a} = \sum F = \vec{F}_g + \vec{n} \]

Extract the x- and y-components from the second law:

\[ (1) \quad ma_x = \sum F_x = mg \sin \theta \]
\[ (2) \quad 0 = \sum F_y = -mg \cos \theta + n \]

Divide Equation (1) by \( m \) and substitute the given values:
\[ a_x = g \sin \theta = (9.80 \text{ m/s}^2) \sin 20.0^\circ = 3.35 \text{ m/s}^2 \]

(b) Find the time taken for the car to reach the bottom.

Use Equation 3.11b for displacement, with \( v_{0x} = 0 \):
\[ \Delta x = \frac{1}{2} a_t^2 \quad \rightarrow \quad \frac{1}{2}(3.35 \text{ m/s}^2)(3.86 \text{ s})^2 = 25.0 \text{ m} \]
\[ t = 3.86 \text{ s} \]

(c) Find the speed of the car at the bottom of the driveway.

Use Equation 3.11a for velocity, again with \( v_{0x} = 0 \):
\[ v_x = a_t t = (3.35 \text{ m/s}^2)(3.86 \text{ s}) = 12.9 \text{ m/s} \]

Remarks Notice that the final answer for the acceleration depends only on \( g \) and the angle \( \theta \), not the mass. Equation (2), which gives the normal force, isn’t useful here, but is essential when friction plays a role.

QUESTION 4.8
If the car is parked on a more gentle slope, how will the time required for it to slide to the bottom of the hill be affected? Explain.

EXERCISE 4.8
(a) Suppose a hockey puck slides down a frictionless ramp with an acceleration of 5.00 \text{ m/s}^2. What angle does the ramp make with respect to the horizontal? (b) If the ramp has a length of 6.00 m, how long does it take the puck to reach the bottom? (c) Now suppose the mass of the puck is doubled. What’s the puck’s new acceleration down the ramp?

Answer (a) 30.7\(^\circ\) (b) 1.55 s (c) unchanged, 5.00 \text{ m/s}^2

EXAMPLE 4.9 Weighing a Fish in an Elevator

Goal Explore the effect of acceleration on the apparent weight of an object.

Problem A man weighs a fish with a spring scale attached to the ceiling of an elevator, as shown in Figure 4.17a. While the elevator is at rest, he measures a weight of 40.0 N. (a) What weight does the scale read if the elevator accelerates upward at 2.00 \text{ m/s}^2? (b) What does the scale read if the elevator accelerates downward at 2.00 \text{ m/s}^2, as in Figure 4.17b? (c) If the elevator cable breaks, what does the scale read?

Strategy Write down Newton’s second law for the fish, including the force \( \vec{T} \) exerted by the spring scale and the force of gravity, \( mg \). The scale doesn’t measure the true weight, it measures the force \( T \) that it exerts on the fish, so in each case solve for this force, which is the apparent weight as measured by the scale.

FIGURE 4.17 (Example 4.9)
The Laws of Motion

Remark
Notice how important it is to have correct signs in this problem! Accelerations can increase or decrease the apparent weight of an object. Astronauts experience very large changes in apparent weight, from several times normal weight during ascent to weightlessness in free fall.

QUESTION 4.9
Starting from rest, an elevator accelerates upward, reaching and maintaining a constant velocity thereafter until it reaches the desired floor, when it begins to slow down. Describe the scale reading during this time.

EXERCISE 4.9
Find the initial acceleration of a rocket if the astronauts on board experience eight times their normal weight during an initial vertical ascent. (Hint: In this exercise, the scale force is replaced by the normal force.)

Answer 68.6 m/s²

EXAMPLE 4.10 Atwood’s Machine

Goal Use the second law to solve a simple two-body problem symbolically.

Problem Two objects of mass \( m_1 \) and \( m_2 \), with \( m_2 > m_1 \), are connected by a light, inextensible cord and hung over a frictionless pulley, as in Active Figure 4.18a. Both cord and pulley have negligible mass. Find the magnitude of the acceleration of the system and the tension in the cord.

Strategy The heavier mass, \( m_2 \), accelerates downward, in the negative \( y \)-direction. Because the cord can’t be stretched, the accelerations of the two masses are equal in magnitude, but opposite in direction, so that \( a_1 \) is positive and \( a_2 \) is negative, and \( a_1 = -a_2 \). Each mass is acted on by a force of tension \( T \) in the upward direction and a force of gravity in the downward direction. Active Figure 4.18b shows free-body diagrams for the two masses. Newton’s second law for each mass, together with the equation relating the accelerations, constitutes a set of three equations for the three unknowns—\( a_1 \), \( a_2 \), and \( T \).

\[
ma = \sum F = T - mg
\]

Solve for \( T \):

\[
T = ma + mg = m(a + g)
\]

Find the mass of the fish from its weight of 40.0 N:

\[
m = \frac{w}{g} = \frac{40.0 \text{ N}}{9.80 \text{ m/s}^2} = 4.08 \text{ kg}
\]

Compute the value of \( T \), substituting \( a = +2.00 \text{ m/s}^2 \):

\[
T = m(a + g) = (4.08 \text{ kg})(2.00 \text{ m/s}^2 + 9.80 \text{ m/s}^2)
\]

\[
= 48.1 \text{ N}
\]

Solution
(a) Find the scale reading as the elevator accelerates upward, as in Figure 4.17a.

Apply Newton’s second law to the fish, taking upward as the positive direction:

\[
ma = \sum F = T - mg
\]

Solve for \( T \):

\[
T = ma + mg = m(a + g)
\]

Find the mass of the fish from its weight of 40.0 N:

\[
m = \frac{w}{g} = \frac{40.0 \text{ N}}{9.80 \text{ m/s}^2} = 4.08 \text{ kg}
\]

Compute the value of \( T \), substituting \( a = +2.00 \text{ m/s}^2 \):

\[
T = m(a + g) = (4.08 \text{ kg})(2.00 \text{ m/s}^2 + 9.80 \text{ m/s}^2)
\]

\[
= 48.1 \text{ N}
\]

(b) Find the scale reading as the elevator accelerates downward, as in Figure 4.17b.

The analysis is the same, the only change being the acceleration, which is now negative: \( a = -2.00 \text{ m/s}^2 \).

\[
T = m(a + g) = (4.08 \text{ kg})(-2.00 \text{ m/s}^2 + 9.80 \text{ m/s}^2)
\]

\[
= 31.8 \text{ N}
\]

(c) Find the scale reading after the elevator cable breaks. Now \( a = -9.80 \text{ m/s}^2 \), the acceleration due to gravity:

\[
T = m(a + g) = (4.08 \text{ kg})(-9.80 \text{ m/s}^2 + 9.80 \text{ m/s}^2)
\]

\[
= 0 \text{ N}
\]

Remarks Notice how important it is to have correct signs in this problem! Accelerations can increase or decrease the apparent weight of an object. Astronauts experience very large changes in apparent weight, from several times normal weight during ascent to weightlessness in free fall.

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Answer 68.6 m/s²

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Strategy The heavier mass, \( m_2 \), accelerates downward, in the negative \( y \)-direction. Because the cord can’t be stretched, the accelerations of the two masses are equal in magnitude, but opposite in direction, so that \( a_1 \) is positive and \( a_2 \) is negative, and \( a_1 = -a_2 \). Each mass is acted on by a force of tension \( T \) in the upward direction and a force of gravity in the downward direction. Active Figure 4.18b shows free-body diagrams for the two masses. Newton’s second law for each mass, together with the equation relating the accelerations, constitutes a set of three equations for the three unknowns—\( a_1 \), \( a_2 \), and \( T \).

\[
ma = \sum F = T - mg
\]

Solve for \( T \):

\[
T = ma + mg = m(a + g)
\]

Find the mass of the fish from its weight of 40.0 N:

\[
m = \frac{w}{g} = \frac{40.0 \text{ N}}{9.80 \text{ m/s}^2} = 4.08 \text{ kg}
\]

Compute the value of \( T \), substituting \( a = +2.00 \text{ m/s}^2 \):

\[
T = m(a + g) = (4.08 \text{ kg})(2.00 \text{ m/s}^2 + 9.80 \text{ m/s}^2)
\]

\[
= 48.1 \text{ N}
\]

(b) Find the scale reading as the elevator accelerates downward, as in Figure 4.17b.

The analysis is the same, the only change being the acceleration, which is now negative: \( a = -2.00 \text{ m/s}^2 \).

\[
T = m(a + g) = (4.08 \text{ kg})(-2.00 \text{ m/s}^2 + 9.80 \text{ m/s}^2)
\]

\[
= 31.8 \text{ N}
\]

(c) Find the scale reading after the elevator cable breaks. Now \( a = -9.80 \text{ m/s}^2 \), the acceleration due to gravity:

\[
T = m(a + g) = (4.08 \text{ kg})(-9.80 \text{ m/s}^2 + 9.80 \text{ m/s}^2)
\]

\[
= 0 \text{ N}
\]

Remarks Notice how important it is to have correct signs in this problem! Accelerations can increase or decrease the apparent weight of an object. Astronauts experience very large changes in apparent weight, from several times normal weight during ascent to weightlessness in free fall.

QUESTION 4.9
Starting from rest, an elevator accelerates upward, reaching and maintaining a constant velocity thereafter until it reaches the desired floor, when it begins to slow down. Describe the scale reading during this time.

EXERCISE 4.9
Find the initial acceleration of a rocket if the astronauts on board experience eight times their normal weight during an initial vertical ascent. (Hint: In this exercise, the scale force is replaced by the normal force.)

Answer 68.6 m/s²
Solution
Apply the second law to each of the two masses individually:

\[ m_1 a_1 = T - m_1 g \]  \hspace{1cm} (1) \hspace{1cm} \[ m_2 a_2 = T - m_2 g \]  \hspace{1cm} (2)

Substitute \( a_2 = -a_1 \) into Equation (2) and multiply both sides by \(-1\):

\[ m_2 a_1 = -T + m_2 g \]  \hspace{1cm} (3)

Add Equations (1) and (3), and solve for \( a_1 \):

\[
\begin{align*}
(m_1 + m_2) a_1 &= m_2 g - m_1 g \\
\frac{m_2 - m_1}{m_1 + m_2} g &= a_1
\end{align*}
\]

Substitute this result into Equation (1) to find \( T \):

\[
T = \left( \frac{2m_1 m_2}{m_1 + m_2} \right) g
\]

Remarks
The acceleration of the second block is the same as that of the first, but negative. When \( m_2 \) gets very large compared with \( m_1 \), the acceleration of the system approaches \( g \), as expected, because \( m_2 \) is falling nearly freely under the influence of gravity. Indeed, \( m_2 \) is only slightly restrained by the much lighter \( m_1 \).

QUESTION 4.10
How could this simple machine be used to raise objects too heavy for a person to lift?

EXERCISE 4.10
Suppose in the same Atwood setup another string is attached to the bottom of \( m_1 \) and a constant force \( f \) is applied, retarding the upward motion of \( m_1 \). If \( m_1 = 5.00 \text{ kg} \) and \( m_2 = 10.00 \text{ kg} \), what value of \( f \) will reduce the acceleration of the system by 50%?

Answer: 24.5 N

4.6 Forces of Friction

An object moving on a surface or through a viscous medium such as air or water encounters resistance as it interacts with its surroundings. This resistance is called friction. Forces of friction are essential in our everyday lives. Friction makes it possible to grip and hold things, drive a car, walk, and run. Even standing in one spot would be impossible without friction, as the slightest shift would instantly cause you to slip and fall.

Imagine that you've filled a plastic trash can with yard clippings and want to drag the can across the surface of your concrete patio. If you apply an external horizontal force \( \vec{F} \) to the can, acting to the right as shown in Active Figure 4.19a (page 102), the can remains stationary if \( \vec{F} \) is small. The force that counteracts \( \vec{F} \) and keeps the can from moving acts to the left, opposite the direction of \( \vec{F} \), and is called the force of static friction, \( \vec{f}_s \). As long as the can isn’t moving, \( \vec{f}_s = -\vec{F} \). If \( \vec{F} \) is increased, \( \vec{f}_s \) also increases. Likewise, if \( \vec{F} \) decreases, \( \vec{f}_s \) decreases. Experiments show that the friction force arises from the nature of the two surfaces: Because of their roughness, contact is made at only a few points, as shown in the magnified view of the surfaces in Active Figure 4.19a.

If we increase the magnitude of \( \vec{F} \), as in Active Figure 4.19b, the trash can eventually slips. When the can is on the verge of slipping, \( f_s \) is a maximum, as shown in Figure 4.19c. When \( F \) exceeds \( f_{s\text{max}} \), the can accelerates to the right. When the can is in motion, the friction force is less than \( f_{s\text{max}} \) (Fig. 4.19c). We call the friction force for an object in motion the force of kinetic friction, \( \vec{f}_k \). The net force \( F - f_k \) in the \( x \)-direction produces an acceleration to the right, according to Newton’s
second law. If \( F = f_s \), the acceleration is zero, and the can moves to the right with constant speed. If the applied force is removed, the friction force acting to the left provides an acceleration of the can in the \(-x\)-direction and eventually brings it to rest, again consistent with Newton’s second law.

Experimentally, to a good approximation, both \( f_{s,\text{max}} \) and \( f_k \) for an object on a surface are proportional to the normal force exerted by the surface on the object. The experimental observations can be summarized as follows:

- The magnitude of the force of static friction between any two surfaces in contact can have the values
  \[
  f_s = \mu_s n
  \]
  where the dimensionless constant \( \mu_s \) is called the coefficient of static friction and \( n \) is the magnitude of the normal force exerted by one surface on the other. Equation 4.11 also holds for \( f_s = f_{s,\text{max}} = \mu_s n \) when an object is on the verge of slipping. This situation is called impending motion. The strict inequality holds when the component of the applied force parallel to the surfaces is less than \( \mu_s n \).

- The magnitude of the force of kinetic friction acting between two surfaces is
  \[
  f_k = \mu_k n
  \]
  where \( \mu_k \) is the coefficient of kinetic friction.

- The values of \( \mu_s \) and \( \mu_k \) depend on the nature of the surfaces, but \( \mu_k \) is generally less than \( \mu_s \). Table 4.2 lists some reported values.

- The direction of the friction force exerted by a surface on an object is opposite the actual motion (kinetic friction) or the impending motion (static friction) of the object relative to the surface.

- The coefficients of friction are nearly independent of the area of contact between the surfaces.

Although the coefficient of kinetic friction varies with the speed of the object, we will neglect any such variations. The approximate nature of Equations 4.11 and 4.12 is easily demonstrated by trying to get an object to slide down an incline at constant acceleration. Especially at low speeds, the motion is likely to be characterized by alternate stick and slip episodes.
TABLE 4.2

Coefficients of Friction

<table>
<thead>
<tr>
<th>Surface Type</th>
<th>$\mu_s$</th>
<th>$\mu_k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel on steel</td>
<td>0.74</td>
<td>0.57</td>
</tr>
<tr>
<td>Aluminum on steel</td>
<td>0.61</td>
<td>0.47</td>
</tr>
<tr>
<td>Copper on steel</td>
<td>0.53</td>
<td>0.36</td>
</tr>
<tr>
<td>Rubber on concrete</td>
<td>1.0</td>
<td>0.8</td>
</tr>
<tr>
<td>Wood on wood</td>
<td>0.25–0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>Glass on glass</td>
<td>0.94</td>
<td>0.4</td>
</tr>
<tr>
<td>Wax wood on wet snow</td>
<td>0.14</td>
<td>0.1</td>
</tr>
<tr>
<td>Wax wood on dry snow</td>
<td>—</td>
<td>0.04</td>
</tr>
<tr>
<td>Metal on metal (lubricated)</td>
<td>0.15</td>
<td>0.06</td>
</tr>
<tr>
<td>Ice on ice</td>
<td>0.1</td>
<td>0.03</td>
</tr>
<tr>
<td>Teflon on Teflon</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Synovial joints in humans</td>
<td>0.01</td>
<td>0.003</td>
</tr>
</tbody>
</table>

*All values are approximate.

QUICK QUIZ 4.6 If you press a book flat against a vertical wall with your hand, in what direction is the friction force exerted by the wall on the book? (a) downward (b) upward (c) out from the wall (d) into the wall

QUICK QUIZ 4.7 A crate is sitting in the center of a flatbed truck. As the truck accelerates to the east, the crate moves with it, not sliding on the bed of the truck. In what direction is the friction force exerted by the bed of the truck on the crate? (a) To the west. (b) To the east. (c) There is no friction force, because the crate isn’t sliding.

QUICK QUIZ 4.8 Suppose your friend is sitting on a sled and asks you to move her across a flat, horizontal field. You have a choice of (a) pushing her from behind by applying a force downward on her shoulders at 30° below the horizontal (Fig. 4.20a) or (b) attaching a rope to the front of the sled and pulling with a force at 30° above the horizontal (Fig 4.20b). Which option would be easier and why?

EXAMPLE 4.11 A Block on a Ramp

Goal Apply the concept of static friction to an object resting on an incline.

Problem Suppose a block with a mass of 2.50 kg is resting on a ramp. If the coefficient of static friction between the block and ramp is 0.350, what maximum angle can the ramp make with the horizontal before the block starts to slip down?

Strategy This is an application of Newton’s second law involving an object in equilibrium. Choose tilted coordinates, as in Figure 4.21. Use the fact that the block is just about to slip when the force of static friction takes its maximum value, $f_s = \mu_s n$.

Solution Write Newton’s laws for a static system in component form. The gravity force has two components, just as in Examples 4.6 and 4.8.

$$\sum F_x = mg \sin \theta - \mu_s n = 0$$

$$\sum F_y = n - mg \cos \theta = 0$$
Rearrange Equation (2) to get an expression for the normal force \( n \):
\[
n = mg \cos \theta
\]

Substitute the expression for \( n \) into Equation (1) and solve for \( \tan \theta \):
\[
\sum F_x = mg \sin \theta - \mu_s mg \cos \theta = 0 \quad \rightarrow \quad \tan \theta = \mu_s
\]

Apply the inverse tangent function to get the answer:
\[
\tan \theta = 0.350 \quad \rightarrow \quad \theta = \tan^{-1} (0.350) = 19.3^\circ
\]

**Remark** It’s interesting that the final result depends only on the coefficient of static friction. Notice also how similar Equations (1) and (2) are to the equations developed in Examples 4.6 and 4.8. Recognizing such patterns is key to solving problems successfully.

**QUESTION 4.11**
How would a larger static friction coefficient affect the maximum angle?

**EXERCISE 4.11**
The ramp in Example 4.11 is roughed up and the experiment repeated. (a) What is the new coefficient of static friction if the maximum angle turns out to be 30.0°? (b) Find the maximum static friction force that acts on the block.

**Answer** (a) 0.577 (b) 12.2 N

---

**EXAMPLE 4.12  The Sliding Hockey Puck**

**Goal** Apply the concept of kinetic friction.

**Problem** The hockey puck in Figure 4.22, struck by a hockey stick, is given an initial speed of 20.0 m/s on a frozen pond. The puck remains on the ice and slides 1.20 \( \times \) \( 10^2 \) m, slowing down steadily until it comes to rest. Determine the coefficient of kinetic friction between the puck and the ice.

**Strategy** The puck slows “steadily,” which means that the acceleration is constant. Consequently, we can use the kinematic equation \( v^2 = v_0^2 + 2a \Delta x \) to find \( a \), the acceleration in the \( x \)-direction. The \( x \) - and \( y \)-components of Newton’s second law then give two equations and two unknowns for the coefficient of kinetic friction, \( \mu_k \), and the normal force \( n \).

**Solution** Solve the time-independent kinematic equation for the acceleration \( a \):
\[
v^2 = v_0^2 + 2a \Delta x
\]
\[
a = \frac{v^2 - v_0^2}{2 \Delta x}
\]

Substitute \( v = 0 \), \( v_0 = 20.0 \) m/s, and \( \Delta x = 1.20 \times 10^2 \) m. Note the negative sign in the answer: \( \vec{a} \) is opposite \( \vec{v} \):
\[
a = \frac{0 - (20.0 \text{ m/s})^2}{2(1.20 \times 10^2 \text{ m})} = -1.67 \text{ m/s}^2
\]

Find the normal force from the \( y \)-component of the second law:
\[
\sum F_y = n - F_y = n - mg = 0
\]
\[
n = mg
\]

Obtain an expression for the force of kinetic friction, and substitute it into the \( x \)-component of the second law:
\[
f_k = \mu_k n = \mu_k mg
\]
\[
ama = \sum F_x = -f_k = -\mu_k mg
\]
Solve for $\mu_k$ and substitute values:

$$\mu_k = \frac{a}{g} = \frac{1.67 \text{ m/s}^2}{9.80 \text{ m/s}^2} = 0.170$$

**Remarks** Notice how the problem breaks down into three parts: kinematics, Newton's second law in the $y$-direction, and then Newton's law in the $x$-direction.

**QUESTION 4.12**

How would the answer be affected if the puck were struck by an astronaut on a patch of ice on Mars, where the acceleration of gravity is $0.35g$, with all other given quantities remaining the same?

**EXERCISE 4.12**

An experimental rocket plane lands on skids on a dry lake bed. If it’s traveling at 80.0 m/s when it touches down, how far does it slide before coming to rest? Assume the coefficient of kinetic friction between the skids and the lake bed is 0.600.

**Answer** 544 m

Two-body problems can often be treated as single objects and solved with a system approach. When the objects are rigidly connected—say, by a string of negligible mass that doesn't stretch—this approach can greatly simplify the analysis. When the two bodies are considered together, one or more of the forces end up becoming forces that are internal to the system, rather than external forces affecting each of the individual bodies. Both approaches will be used in Example 4.13.

**EXAMPLE 4.13 Connected Objects**

**Goal** Use both the general method and the system approach to solve a connected two-body problem involving gravity and friction.

**Problem** (a) A block with mass $m_1 = 4.00$ kg and a ball with mass $m_2 = 7.00$ kg are connected by a light string that passes over a frictionless pulley, as shown in Figure 4.23a. The coefficient of kinetic friction between the block and the surface is 0.300. Find the acceleration of the two objects and the tension in the string. (b) Check the answer for the acceleration by using the system approach.

**Strategy** Connected objects are handled by applying Newton's second law separately to each object. The free-body diagrams for the block and the ball are shown in Figure 4.23b, with the $+x$-direction to the right and the $+y$-direction upwards. The magnitude of the acceleration for both objects has the same value, $|a_1| = |a_2| = a$. The block with mass $m_1$ moves in the positive $x$-direction, and the ball with mass $m_2$ moves in the negative $y$-direction, so $a_1 = -a_2$. Using Newton's second law, we can develop two equations involving the unknowns $T$ and $a$ that can be solved simultaneously. In part (b), treat the two masses as a single object, with the gravity force on the ball increasing the combined object's speed and the friction force on the block retarding it. The tension forces then become internal and don’t appear in the second law.

**Solution**

(a) Find the acceleration of the objects and the tension in the string.

Write the components of Newton’s second law for the block of mass $m_1$:

$$\sum F_x = T - f_k = m_1a_1$$

$$\sum F_y = n - m_1g = 0$$

The equation for the $y$-component gives $n = m_1g$. Substitute this value for $n$ and $f_k = \mu_k n$ into the equation for the $x$-component:

$$T - \mu_k m_1 g = m_1 a_1$$

(b) Check the answer for the acceleration by using the system approach.
Applies Newton’s second law to the ball, recalling that \( a_2 = -a_1 \):

\[
\sum F_j = -m_2 g + T = m_2 a_2 = -m_2 a_1
\]

Subtract Equation (2) from Equation (1), eliminating \( T \) and leaving an equation that can be solved for \( a_1 \):

\[
a_1 = \frac{(7.00 \text{ kg})(9.80 \text{ m/s}^2) - (0.300)(4.00 \text{ kg})(9.80 \text{ m/s}^2)}{(4.00 \text{ kg} + 7.00 \text{ kg})}
\]

\[
= 5.17 \text{ m/s}^2
\]

Substitute the given values to obtain the acceleration:

\[
T = 32.4 \text{ N}
\]

(b) Find the acceleration using the system approach, where the system consists of the two blocks.

Apply Newton’s second law to the system and solve for \( a \):

\[
(m_1 + m_2) a = m_2 g - \mu_s n = m_2 g - \mu_s m_1 g
\]

\[
a = \frac{m_2 g - \mu_s m_1 g}{m_1 + m_2}
\]

Remarks: Although the system approach appears quick and easy, it can be applied only in special cases and can’t give any information about the internal forces, such as the tension. To find the tension, you must consider the free-body diagram of one of the blocks separately.

QUESTION 4.13

If mass \( m_2 \) is increased, does the acceleration of the system increase, decrease, or remain the same? Does the tension increase, decrease, or remain the same?

EXERCISE 4.13

What if an additional mass is attached to the ball in Example 4.13? How large must this mass be to increase the downward acceleration by 50%? Why isn’t it possible to add enough mass to double the acceleration?

Answer: 14.0 kg. Doubling the acceleration to 10.3 m/s\(^2\) isn’t possible simply by suspending more mass because all objects, regardless of their mass, fall freely at 9.8 m/s\(^2\) near the Earth’s surface.

EXAMPLE 4.14 Two Blocks and a Cord

Goal: Apply Newton’s second law and static friction in a two-body system.

Problem: A block of mass 5.00 kg rides on top of a second block of mass 10.0 kg. A person attaches a string to the bottom block and pulls the system horizontally across a frictionless surface, as in Figure 4.24a. Friction between the two blocks keeps the 5.00-kg block from slipping off. If the coefficient of static friction is 0.350, what maximum force can be exerted by the string on the 10.0-kg block without causing the 5.00-kg block to slip?

Strategy: Draw a free-body diagram for each block. The static friction force causes the top block to move horizontally, and the maximum such force corresponds to \( f_s = \mu_s n \). This same static friction retards the motion of the bottom block. As long as the top block isn’t slipping, the acceleration of both blocks is the same. Write Newton’s second law for each block, and eliminate the acceleration \( a \) by substitution, solving for the tension \( T \).
forces of friction

Solution

Write the two components of Newton’s second law for the top block:

\[ \text{x-component: } ma = \mu_n n_1 \]
\[ \text{y-component: } 0 = n_1 - mg \]

Solve the y-component for \( n_1 \), substitute the result into the x-component, and then solve for \( a \):

\[ n_1 = mg \rightarrow ma = \mu_n mg \rightarrow a = \mu_n g \]

Write the x-component of Newton’s second law for the bottom block:

\[ Ma = -\mu_n mg + T \]

Substitute the expression for \( a = \mu_n g \) into Equation (1)

\[ M\mu_n g = T - \mu_n mg \rightarrow T = (m + M)\mu_n g \]

Now evaluate to get the answer:

\[ T = (5.00 \text{ kg} + 10.0 \text{ kg})(0.350)(9.80 \text{ m/s}^2) = 51.5 \text{ N} \]

Remarks Notice that the y-component for the 10.0-kg block wasn’t needed because there was no friction between that block and the underlying surface. It’s also interesting to note that the top block was accelerated by the force of static friction.

QUESTION 4.14

What would happen if the tension force exceeded 51.5 N?

EXERCISE 4.14

Suppose instead the string is attached to the top block in Example 14.4 (see Fig. 4.24b). Find the maximum force that can be exerted by the string on the block without causing the top block to slip.

Answer 25.7 N

**APPLYING PHYSICS 4.1 CARS AND FRICTION**

Forces of friction are important in the analysis of the motion of cars and other wheeled vehicles. How do such forces both help and hinder the motion of a car?

**Explanation** There are several types of friction forces to consider, the main ones being the force of friction between the tires and the road surface and the retarding force produced by air resistance.

Assuming the car is a four-wheel-drive vehicle of mass \( m \), as each wheel turns to propel the car forward, the tire exerts a rearward force on the road. The reaction to this rearward force is a forward force \( \vec{f} \) exerted by the road on the tire (Fig. 4.25).

If we assume the same forward force \( \vec{f} \) is exerted on each tire, the net forward force on the car is \( 4\vec{f} \), and the car’s acceleration is therefore \( \vec{a} = 4\vec{f}/m \).

The friction between the moving car’s wheels and the road is normally static friction, unless the car is skidding.

When the car is in motion, we must also consider the force of air resistance, \( \vec{R} \), which acts in the direction opposite the velocity of the car. The net force exerted on the car is therefore \( 4\vec{f} - \vec{R} \), so the car’s acceleration is \( \vec{a} = (4\vec{f} - \vec{R})/m \). At normal driving speeds, the magnitude of \( \vec{R} \) is proportional to the first power of the speed, \( \vec{R} = bv \), where \( b \) is a constant, so the force of air resistance increases with increasing speed. When \( \vec{R} \) is equal to \( 4\vec{f} \), the acceleration is zero and the car moves at a constant speed. To minimize this resistive force, racing cars often have very low profiles and streamlined contours.

**FIGURE 4.25** (Applying Physics 4.1) The horizontal forces acting on the car are the forward forces \( \vec{f} \) exerted by the road on each tire and the force of air resistance \( \vec{R} \), which acts opposite the car’s velocity. (The car’s tires exert a rearward force on the road, not shown in the diagram.)
Air resistance isn’t always undesirable. What are some applications that depend on it?

**Explanation** Consider a skydiver plunging through the air, as in Figure 4.26. Despite falling from a height of several thousand meters, she never exceeds a speed of around 120 miles per hour. This is because, aside from the downward force of gravity $mg$, there is also an upward force of air resistance, $R$. Before she reaches a final constant speed, the magnitude of $R$ is less than her weight. As her downward speed increases, the force of air resistance increases. The vector sum of the force of gravity and the force of air resistance gives a total force that decreases with time, so her acceleration decreases. Once the two forces balance each other, the net force is zero, so the acceleration is zero, and she reaches a *terminal speed*.

Terminal speed is generally still high enough to be fatal on impact, although there have been amazing stories of survival. In one case, a man fell flat on his back in a freshly plowed field and survived. (He did, however, break virtually every bone in his body.) In another case, a flight attendant survived a fall from thirty thousand feet into a snowbank. In neither case would the person have had any chance of surviving without the effects of air drag.

Parachutes and paragliders create a much larger drag force due to their large area and can reduce the terminal speed to a few meters per second. Some sports enthusiasts have even developed special suits with wings, allowing a long glide to the ground. In each case, a larger cross-sectional area intercepts more air, creating greater air drag, so the terminal speed is lower.

Air drag is also important in space travel. Without it, returning to Earth would require a considerable amount of fuel. Air drag helps slow capsules and spaceships, and aerocapture techniques have been proposed for trips to other planets. These techniques significantly reduce fuel requirements by using air drag to slow the spacecraft down.

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**APPLICATIONING PHYSICS 4.2 AIR DRAG**

Parachutes and paragliders create a much larger drag force due to their large area and can reduce the terminal speed to a few meters per second. Some sports enthusiasts have even developed special suits with wings, allowing a long glide to the ground. In each case, a larger cross-sectional area intercepts more air, creating greater air drag, so the terminal speed is lower.

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**SUMMARY**

### 4.1 Forces

There are four known fundamental forces of nature: (1) the strong nuclear force between subatomic particles; (2) the electromagnetic forces between electric charges; (3) the weak nuclear forces, which arise in certain radioactive decay processes; and (4) the gravitational force between objects. These are collectively called field forces. Classical physics deals only with the gravitational and electromagnetic forces.

Forces such as friction or that characterizing a bat hitting a ball are called contact forces. On a more fundamental level, contact forces have an electromagnetic nature.

### 4.2 Newton’s First Law

Newton’s first law states that an object moves at constant velocity unless acted on by a force.

The tendency for an object to maintain its original state of motion is called *inertia*. *Mass* is the physical quantity that measures the resistance of an object to changes in its velocity.

### 4.3 Newton’s Second Law

Newton’s second law states that the acceleration of an object is directly proportional to the net force acting on it and inversely proportional to its mass. The net force acting on an object equals the product of its mass and acceleration:

$$ \sum \vec{F} = m\vec{a} \quad [4.1] $$

Newton’s universal law of gravitation is

$$ F_g = G \frac{m_1 m_2}{r^2} \quad [4.5] $$

The weight $w$ of an object is the magnitude of the force of gravity exerted on that object and is given by

$$ w = mg \quad [4.6] $$

where $g = F_g/m$ is the acceleration of gravity near Earth’s surface.

Solving problems with Newton’s second law involves finding all the forces acting on a system and writing Equa-
4.4 Newton’s Third Law

Newton’s third law states that if two objects interact, the force \( \mathbf{F}_{12} \) exerted by object 1 on object 2 is equal in magnitude and opposite in direction to the force \( \mathbf{F}_{21} \) exerted by object 2 on object 1:

\[
\mathbf{F}_{12} = -\mathbf{F}_{21}
\]

An isolated force can never occur in nature.

4.5 Applications of Newton’s Laws

An object in equilibrium has no net external force acting on it, and the second law, in component form, implies that \( \Sigma F_x = 0 \) and \( \Sigma F_y = 0 \) for such an object. These two equations are useful for solving problems in statics, in which the object is at rest or moving at constant velocity.

An object under acceleration requires the same two equations, but with the acceleration terms included: \( \Sigma F_x = ma_x \) and \( \Sigma F_y = ma_y \). When the acceleration is constant, the equations of kinematics can supplement Newton’s second law.

### MULTIPLE-CHOICE QUESTIONS

1. A horizontal force of 95.0 N is applied to a 60.0-kg crate on a rough, level surface. If the crate accelerates at 1.20 m/s², what is the magnitude of the force of kinetic friction acting on the crate? (a) 23.0 N  (b) 45.0 N  (c) 16.0 N  (d) 33.0 N  (e) 8.80 N

2. A 70.0-kg man stands on a pedestal of mass 27.0 kg, which rests on a level surface. What is the normal force exerted by the ground on the pedestal? (a) 265 N  (b) 368 N  (c) 478 N  (d) 624 N  (e) 951 N

3. Two monkeys of equal mass are holding onto a single vine of negligible mass that hangs vertically from a tree, with one monkey a few meters higher than the other. What is the ratio of the tension in the vine above the upper monkey to the tension in the vine between the two monkeys? (a) \( \frac{1}{2} \)  (b) 1  (c) 1.5  (d) 2  (e) More information is required.

4. A force of 70.0 N is exerted at an angle of 30.0° below the horizontal on a block of mass 8.00 kg that is resting on a table. What is the magnitude of the normal force acting on the block? (a) 43.4 N  (b) 78.4 N  (c) 113 N  (d) 126 N  (e) 92.4 N

5. If Earth’s mass and radius both suddenly doubled, what would the new value of the acceleration of gravity near Earth’s surface? (a) 9.80 m/s²  (b) 4.90 m/s²  (c) \( 2.45 \) m/s²  (d) 19.6 m/s²  (e) 12.6 m/s²

6. A crate remains stationary after it has been placed on a ramp inclined at an angle with the horizontal. Which of the following statements must be true about the magnitude of the frictional force that acts on the crate? (a) It is larger than the weight of the crate. (b) It is at least equal to the weight of the crate. (c) It is equal to \( \mu_s n \). (d) It is greater than the component of the gravitational force acting down the ramp. (e) It is equal to the component of the gravitational force acting down the ramp.

7. A thrown rock hits a window, breaking the glass, and ends up on the floor inside the room. Which of the following statements are true? (a) The force of the rock on the glass was bigger than the force of the glass on the rock. (b) The force of the rock on the glass had the same magnitude as the force of the glass on the rock. (c) The force of the rock on the glass was less than the force of the glass on the rock. (d) The rock didn’t slow down as it broke the glass. (e) None of these statements is true.

8. A manager of a restaurant pushes horizontally with a force of magnitude 150 N on a box of melons. The box moves across the floor with a constant acceleration in the same direction as the applied force. Which statement is most accurate concerning the magnitude of the force of kinetic friction acting on the box? (a) It is greater than 150 N. (b) It is less than 150 N. (c) It is equal to 150 N. (d) The kinetic friction force is steadily decreasing. (e) The kinetic friction force must be zero.

9. Four forces act on an object, given by \( \mathbf{A} = 40 \) N east, \( \mathbf{B} = 50 \) N north, \( \mathbf{C} = 70 \) N west, and \( \mathbf{D} = 90 \) N south.
What is the magnitude of the net force on the object? (a) 50 N (b) 70 N (c) 131 N (d) 170 N (e) 250 N

If an object of mass \( m \) moves with constant velocity \( v \), the net force on the object is (a) \( mg \) (b) \( mv \) (c) \( ma \) (d) 0 (e) None of these answers is correct.

If an object is in equilibrium, which of the following statements is not true? (a) The speed of the object remains constant. (b) The acceleration of the object is zero. (c) The net force acting on the object is zero. (d) The object must be at rest. (e) The velocity is constant.

A truck loaded with sand accelerates along a highway. The driving force on the truck remains constant. What happens to the acceleration of the truck as its trailer leaks sand at a constant rate through a hole in its bottom? (a) It decreases at a steady rate. (b) It increases at a steady rate. (c) It increases and then decreases. (d) It decreases and then increases. (e) It remains constant.

A large crate of mass \( m \) is placed on the back of a truck but not tied down. As the truck accelerates forward with an acceleration \( a \), the crate remains at rest relative to the truck. What force causes the crate to accelerate forward? (a) the normal force (b) the force of gravity (c) the force of friction between the crate and the floor of the truck (d) the "ma" force (e) none of these

Which of the following statements are true? (a) An astronaut’s weight is the same on the Moon as on Earth. (b) An astronaut’s mass is the same on the International Space Station as it is on Earth. (c) Earth’s gravity has no effect on astronauts inside the International Space Station. (d) An astronaut’s mass is greater on Earth than on the Moon. (e) None of these statements are true.

Two objects are connected by a string that passes over a frictionless pulley as in Active Figure 4.18, where \( m_1 < m_2 \) and \( a_1 \) and \( a_2 \) are the respective magnitudes of the accelerations. Which mathematical statement is true concerning the magnitude of the acceleration \( a_2 \) of mass \( m_2 \)? (a) \( a_2 < g \) (b) \( a_2 > g \) (c) \( a_2 = g \) (d) \( a_2 < a_1 \) (e) \( a_2 > a_1 \)

An object of mass \( m \) undergoes an acceleration \( \vec{a} \) down a rough incline. Which of the following forces should not appear in the free-body diagram for the object? Choose all correct answers. (a) the force of gravity (b) \( m \vec{a} \) (c) the normal force of the incline on the object (d) the force of friction down the incline (e) the force of friction up the incline (f) the force of the object on the incline

1. A ball is held in a person’s hand. (a) Identify all the external forces acting on the ball and the reaction to each. (b) If the ball is dropped, what force is exerted on it while it is falling? Identify the reaction force in this case. (Neglect air resistance.)

2. If gold were sold by weight, would you rather buy it in Denver or in Death Valley? If it were sold by mass, in which of the two locations would you prefer to buy it? Why?

3. If you push on a heavy box that is at rest, you must exert some force to start its motion. However, once the box is sliding, you can apply a smaller force to maintain its motion. Why?

4. A space explorer is moving through space far from any planet or star. He notices a large rock, taken as a specimen from an alien planet, floating around the cabin of the ship. Should he push it gently or should he kick it toward the storage compartment? Why?

5. A passenger sitting in the rear of a bus claims that she was injured as the driver slammed on the brakes, causing a suitcase to come flying toward her from the front of the bus. If you were the judge in this case, what disposition would you make? Why?

6. A weight lifter stands on a bathroom scale. She pumps a barbell up and down. What happens to the reading on the scale? Suppose she is strong enough to actually throw the barbell upward. How does the reading on the scale vary now?

7. What force causes an automobile to move? A propeller-driven airplane? A rowboat?

8. Analyze the motion of a rock dropped in water in terms of its speed and acceleration as it falls. Assume a resistive force is acting on the rock that increases as the velocity of the rock increases.

9. In the motion picture It Happened One Night (Columbia Pictures, 1934), Clark Gable is standing inside a stationary bus in front of Claudette Colbert, who is seated. The bus suddenly starts moving forward and Clark falls into Claudette’s lap. Why did this happen?

10. As a rocket is fired from a launching pad, its speed and acceleration increase with time as its engines continue to operate. Explain why this occurs even though the thrust of the engines remains constant.

11. In a tug-of-war between two athletes, each pulls on the rope with a force of 200 N. What is the tension in the rope? If the rope doesn’t move, what horizontal force does each athlete exert against the ground?

12. Draw a free-body diagram for each of the following objects: (a) a projectile in motion in the presence of air resistance, (b) a rocket leaving the launch pad with its engines operating, (c) an athlete running along a horizontal track.

13. Identify the action–reaction pairs in the following situations: (a) a man takes a step, (b) a snowball hits a girl in the back, (c) a baseball player catches a ball, (d) a gust of wind strikes a window.

14. Suppose you are driving a car at a high speed. Why should you avoid slamming on your brakes when you want to stop in the shortest possible distance? (Newer cars have antilock brakes that avoid this problem.)
The Problems for this chapter may be assigned online at WebAssign.

1, 2, 3 = straightforward, intermediate, challenging
GP = denotes guided problem
ecp = denotes enhanced content problem
S = biomedical application
□ = denotes full solution available in Student Solutions Manual/Study Guide

SECTION 4.1 FORCES

SECTION 4.2 NEWTON’S FIRST LAW

SECTION 4.3 NEWTON’S SECOND LAW

SECTION 4.4 NEWTON’S THIRD LAW

1. The heaviest invertebrate is the giant squid, which is estimated to have a weight of about 2 tons spread out over its length of 70 feet. What is its weight in newtons?

2. A football punter accelerates a football from rest to a speed of 10 m/s during the time in which his toe is in contact with the ball (about 0.20 s). If the football has a mass of 0.50 kg, what average force does the punter exert on the ball?

3. A 6.0-kg object undergoes an acceleration of 2.0 m/s². (a) What is the magnitude of the resultant force acting on it? (b) If this same force is applied to a 4.0-kg object, what acceleration is produced?

4. ecp One or more external forces are exerted on each object enclosed in a dashed box shown in Figure 4.2. Identify the reaction to each of these forces.

5. A bag of sugar weighs 5.00 lb on Earth. What would it weigh in newtons on the Moon, where the free-fall acceleration is one-sixth that on Earth? Repeat for Jupiter, where g is 2.64 times that on Earth. Find the mass of the bag of sugar in kilograms at each of the three locations.

6. A freight train has a mass of 1.5 × 10⁷ kg. If the locomotive can exert a constant pull of 7.5 × 10⁵ N, how long does it take to increase the speed of the train from rest to 80 km/h?

7. The air exerts a forward force of 10 N on the propeller of a 0.20-kg model airplane. If the plane accelerates forward at 2.0 m/s², what is the magnitude of the resistive force exerted by the air on the airplane?

8. ecp Consider a solid metal sphere (S) a few centimeters in diameter and a feather (F). For each quantity in the list that follows, indicate whether the quantity is the same, greater, or lesser in the case of S or in that of F. Explain in each case why you gave the answer you did. Here is the list: (a) the gravitational force, (b) the time it will take to fall a given distance in air, (c) the time it will take to fall a given distance in vacuum, (d) the total force on the object when falling in vacuum.

9. A chinook salmon has a maximum underwater speed of 3.0 m/s, and can jump out of the water vertically with a speed of 6.0 m/s. A record salmon has a length of 1.5 m and a mass of 61 kg. When swimming upward at constant speed, and neglecting buoyancy, the fish experiences three forces: an upward force \( F \) exerted by the tail fin, the downward drag force of the water, and the downward force of gravity. As the fish leaves the surface of the water, however, it experiences a net upward force causing it to accelerate from 3.0 m/s to 6.0 m/s. Assuming the drag force disappears as soon as the head of the fish breaks the surface and \( F \) is exerted until two-thirds of the fish’s length has left the water, determine the magnitude of \( F \).

10. A 5.0-g bullet leaves the muzzle of a rifle with a speed of 320 m/s. What force (assumed constant) is exerted on the bullet while it is traveling down the 0.82-m-long barrel of the rifle?

11. A boat moves through the water with two forces acting on it. One is a 2,000-N forward push by the water on the propeller, and the other is a 1,800-N resistive force due to the water around the bow. (a) What is the acceleration of the 1,000-kg boat? (b) If it starts from rest, how far will the boat move in 10.0 s? (c) What will its velocity be at the end of that time?

12. Two forces are applied to a car in an effort to move it, as shown in Figure P4.12. (a) What is the resultant of these two forces? (b) If the car has a mass of 3,000 kg, what acceleration does it have? Ignore friction.

13. A 65.0-kg skydiver reaches a terminal speed of 55.0 m/s with her parachute undeployed. Suppose the drag force acting on her is proportional to the speed squared, or \( F_{\text{drag}} = kv^2 \). (a) What is the constant of proportionality \( k \)? (Assume the gravitational acceleration is 9.80 m/s².) (b) What was the magnitude of her acceleration when she was falling at half terminal speed?

14. ecp An object of mass \( m \) is dropped from the roof of a building of height \( h \). While the object is falling, a wind blowing parallel to the face of the building exerts a constant horizontal force \( F \) on the object. (a) How long does it take the object to strike the ground? Express the time \( t \) in terms of \( g \) and \( h \). (b) Find an expression in terms of \( m \) and \( F \) for the acceleration \( a_x \) of the object in the horizontal direction (taken as the positive \( x \)-direction). (c) How
15. After falling from rest from a height of 30 m, a 0.50-kg ball rebounds upward, reaching a height of 20 m. If the contact between ball and ground lasted 2.0 ms, what average force was exerted on the ball?

16. The force exerted by the wind on the sails of a sailboat is 390 N north. The water exerts a force of 180 N east. If the boat (including its crew) has a mass of 270 kg, what are the magnitude and direction of its acceleration?

SECTION 4.5 APPLICATIONS OF NEWTON’S LAWS

17. (a) Find the tension in each cable supporting the 600-N cat burglar in Figure P4.17. (b) Suppose the horizontal cable were reattached higher up on the wall. Would the tension in the other cable increase, decrease, or stay the same? Why?

18. A certain orthodontist uses a wire brace to align a patient’s crooked tooth as in Figure P4.18. The tension in the wire is adjusted to have a magnitude of 18.0 N. Find the magnitude of the net force exerted by the wire on the crooked tooth.

19. A 150-N bird feeder is supported by three cables as shown in Figure P4.19. Find the tension in each cable.

20. The leg and cast in Figure P4.20 weigh 220 N (w_1). Determine the weight w_2 and the angle a needed so that no force is exerted on the hip joint by the leg plus the cast.

21. Two blocks each of mass 3.50 kg are fastened to the top of an elevator as in Figure P4.21. (a) If the elevator accelerates upward at 1.60 m/s^2, find the tensions T_1 and T_2 in the upper and lower strings. (b) If the strings can withstand a maximum tension of 85.0 N, what maximum acceleration can the elevator have before the first string breaks?

22. Two blocks each of mass m are fastened to the top of an elevator as in Figure P4.21. The elevator has an upward acceleration a. The strings have negligible mass. (a) Find the tensions T_1 and T_2 in the upper and lower strings in terms of m, a, and g. (b) Compare the two tensions and determine which string would break first if a is made sufficiently large. (c) What are the tensions if the elevator cable breaks?

23. The distance between two telephone poles is 50.0 m. When a 1.00-kg bird lands on the telephone wire midway between the poles, the wire sags 0.200 m. Draw a free-body diagram of the bird. How much tension does the bird produce in the wire? Ignore the weight of the wire.

24. Two people are pulling a boat through the water as in Figure P4.24. Each exerts a force of 600 N directed at a 30.0° angle relative to the forward motion of the boat. If the boat moves with constant velocity, find the resistive force F exerted by the water on the boat.

25. A 5.0-kg bucket of water is raised from a well by a rope. If the upward acceleration of the bucket is 3.0 m/s^2, find the force exerted by the rope on the bucket.

26. A shopper in a supermarket pushes a loaded cart with a horizontal force of 10 N. The cart has a mass of 30 kg. (a) How far will it move in 3.0 s, starting from rest? (Ignore friction.) (b) How far will it move in 3.0 s if the
shelf places his 30-N child in the cart before he begins to push it?

27. A 2000-kg car is slowed down uniformly from 20.0 m/s to 5.00 m/s in 4.00 s. (a) What average force acted on the car during that time, and (b) how far did the car travel during that time?

28. Two packing crates of masses 10.0 kg and 5.00 kg are connected by a light string that passes over a frictionless pulley as in Figure P4.28. The 5.00-kg crate lies on a smooth incline of angle 40.0°. Find the acceleration of the 5.00-kg crate and the tension in the string.

29. Assume the three blocks portrayed in Figure P4.29 move on a frictionless surface and a 42-N force acts as shown on the 3.0-kg block. Determine (a) the acceleration given this system, (b) the tension in the cord connecting the 3.0-kg and the 1.0-kg blocks, and (c) the force exerted by the 1.0-kg block on the 2.0-kg block.

30. An object of mass 2.0 kg starts from rest and slides down an inclined plane 80 cm long in 0.50 s. What net force is acting on the object along the incline?

31. A setup similar to the one shown in Figure P4.31 is often used in hospitals to support and apply a traction force to an injured leg. (a) Determine the force of tension in the rope supporting the leg. (b) What is the traction force exerted on the leg? Assume the traction force is horizontal.

32. Two blocks of masses \( m_1 \) and \( m_2 \) are placed on a frictionless horizontal table and is connected to a cable that passes over a pulley and is then fastened to a hanging object with mass \( m_3 = 10.0 \text{ kg} \), as shown in Figure P4.36. Find the acceleration of each object and the tension in the cable.

33. An 80-kg stuntman jumps from a window of a building situated 30 m above a catching net. Assuming air resistance exerts a 100-N force on the stuntman as he falls, determine his velocity just before he hits the net.

34. Cord A exerts a force on block 1 to make it accelerate forward. (a) How does the magnitude of the force exerted by cord A on block 1 compare with the magnitude of the force exerted by cord B on block 2? (b) How does the acceleration of block 1 compare with the acceleration of block 2? (c) Does cord B exert a force on block 1? Explain your answer.

35. (a) An elevator of mass \( m \) moving upward has two forces acting on it: the upward force of tension in the cable and the downward force due to gravity. When the elevator is accelerating upward, which is greater, \( T \) or \( w \)? (b) When the elevator is moving at a constant velocity upward, which is greater, \( T \) or \( w \)? (c) When the elevator is moving upward, but the acceleration is downward, which is greater, \( T \) or \( w \)? (d) Let the elevator have a mass of 1500 kg and an upward acceleration of 2.5 m/s². Find \( T \). Is your answer consistent with the answer to part (a)? (e) The elevator of part (d) now moves with a constant upward velocity of 10 m/s. Find \( T \). Is your answer consistent with your answer to part (b)? (f) Having initially moved upward with a constant velocity, the elevator begins to accelerate downward at 1.50 m/s². Find \( T \). Is your answer consistent with your answer to part (c)?
37. A 1000-kg car is pulling a 300-kg trailer. Together, the car and trailer have an acceleration of 2.15 m/s² in the forward direction. Neglecting frictional forces on the trailer, determine (a) the net force on the car, (b) the net force on the trailer, (c) the force exerted by the trailer on the car, and (d) the resultant force exerted by the car on the road.

38. Two objects with masses of 3.00 kg and 5.00 kg are connected by a light string that passes over a frictionless pulley, as in Figure P4.38. Determine (a) the tension in the string, (b) the acceleration of each object, and (c) the distance each object will move in the first second of motion if both objects start from rest.

SECTION 4.6 FORCES OF FRICTION

39. A dockworker loading crates on a ship finds that a 20-kg crate, initially at rest on a horizontal surface, requires a 75-N horizontal force to set it in motion. However, after the crate is in motion, a horizontal force of 60 N is required to keep it moving with a constant speed. Find the coefficients of static and kinetic friction between crate and floor.

40. In Figure P4.36, $m_1 = 10$ kg and $m_2 = 4.0$ kg. The coefficient of static friction between $m_1$ and the horizontal surface is 0.50, and the coefficient of kinetic friction is 0.30. (a) If the system is released from rest, what will its acceleration be? (b) If the system is set in motion with $m_2$ moving downward, what will be the acceleration of the system?

41. A 1000-N crate is being pushed across a level floor at a constant speed by a force $\vec{F}$ of 300 N at an angle of 20.0° below the horizontal, as shown in Figure P4.41a. (a) What is the coefficient of kinetic friction between the crate and the floor? (b) If the 300-N force is instead pulling the block at an angle of 20.0° above the horizontal, as shown in Figure P4.41b, what will be the acceleration of the crate? Assume that the coefficient of friction is the same as that found in part (a).

42. A hockey puck is hit on a frozen lake and starts moving with a speed of 12.0 m/s. Five seconds later, its speed is 6.00 m/s. (a) What is its average acceleration? (b) What is the average value of the coefficient of kinetic friction between puck and ice? (c) How far does the puck travel during the 5.00-s-interval?

43. Consider a large truck carrying a heavy load, such as steel beams. A significant hazard for the driver is that the load may slide forward, crushing the cab, if the truck stops suddenly in an accident or even in braking. Assume, for example, a 10000-kg load sits on the flatbed of a 20 000-kg truck moving at 12.0 m/s. Assume the load is not tied down to the truck and has a coefficient of static friction of 0.500 with the truck bed. (a) Calculate the minimum stopping distance for which the load will not slide forward relative to the truck. (b) Is any piece of data unnecessary for the solution?

44. A crate of mass 45.0 kg is being transported on the flatbed of a pickup truck. The coefficient of static friction between the crate and the truck’s flatbed is 0.350, and the coefficient of kinetic friction is 0.320. (a) The truck accelerates forward on level ground. What is the maximum acceleration the truck can have so that the crate does not slide relative to the truck’s flatbed? (b) The truck barely exceeds this acceleration and then moves with constant acceleration, with the crate sliding along its bed. What is the acceleration of the crate relative to the ground?

45. Objects with masses $m_1 = 10.0$ kg and $m_2 = 5.00$ kg are connected by a light string that passes over a frictionless pulley as in Figure P4.36. If, when the system starts from rest, $m_2$ falls 1.00 m in 1.20 s, determine the coefficient of kinetic friction between $m_1$ and the table.

46. A hockey puck struck by a hockey stick is given an initial speed $v_0$ in the positive $x$-direction. The coefficient of kinetic friction between the ice and the puck is $\mu_k$. (a) Obtain an expression for the acceleration of the puck. (b) Use the result of part (a) to obtain an expression for the distance $d$ the puck slides. The answer should be in terms of the variables $v_0$, $\mu_k$, and $g$ only.

47. The coefficient of static friction between the 3.00-kg crate and the 35.0° incline of Figure P4.47 is 0.300. What minimum force $\vec{F}$ must be applied to the crate perpendicular to the incline to prevent the crate from sliding down the incline?

48. A student decides to move a box of books into her dormitory room by pulling on a rope attached to the box. She pulls with a force of 80.0 N at an angle of 25.0° above the horizontal. The box has a mass of 25.0 kg, and the coefficient of kinetic friction between box and floor is 0.300. (a) Find the acceleration of the box. (b) The student now starts moving the box up a 10.0° incline, keeping her 80.0 N force directed at 25.0° above the line of the incline. If the coefficient of friction is unchanged, what is the new acceleration of the box?

49. An object falling under the pull of gravity is acted upon by a frictional force of air resistance. The magnitude of this force is approximately proportional to the...
speed of the object, which can be written as $f = bv$. Assume $b = 15 \text{ kg/s}$ and $m = 50 \text{ kg}$. (a) What is the terminal speed the object reaches while falling? (b) Does your answer to part (a) depend on the initial speed of the object? Explain.

50. A car is traveling at 50.0 km/h on a flat highway. (a) If the coefficient of friction between road and tires on a rainy day is 0.100, what is the minimum distance in which the car will stop? (b) What is the stopping distance when the surface is dry and the coefficient of friction is 0.600?

51. A 3.00-kg block starts from rest at the top of a 30.0° incline and slides 2.00 m down the incline in 1.50 s. Find (a) the acceleration of the block, (b) the coefficient of kinetic friction between the block and the incline, (c) the frictional force acting on the block, and (d) the speed of the block after it has slid 2.00 m.

52. A 2.00-kg block is held in equilibrium on an incline of angle $\theta = 60.0°$ by a horizontal force $F$ applied in the direction shown in Figure P4.52. If the coefficient of static friction between block and incline is $\mu_s = 0.300$, determine (a) the minimum value of $F$ and (b) the normal force exerted by the incline on the block.

53. Find the acceleration reached by each of the two objects shown in Figure P4.53 if the coefficient of kinetic friction between the 7.00-kg object and the plane is 0.250.

54. Objects of masses $m_1 = 4.00 \text{ kg}$ and $m_2 = 9.00 \text{ kg}$ are connected by a light string that passes over a frictionless pulley as in Figure P4.54. The object $m_1$ is held at rest on the floor, and $m_2$ rests on a fixed incline of $\theta = 40.0°$. The objects are released from rest, and $m_1$ slides 1.00 m down the incline in 4.00 s. Determine (a) the acceleration of each object, (b) the tension in the string, and (c) the coefficient of friction between $m_1$ and the incline.

55. The person in Figure P4.55 weighs 170 lb. Each crutch makes an angle of 22.0° with the vertical (as seen from the front). Half of the person’s weight is supported by the crutches, the other half by the vertical forces exerted by the ground on his feet. Assuming he is at rest and the force exerted by the ground on the crutches acts along the crutches, determine (a) the smallest possible coefficient of friction between crutches and ground and (b) the magnitude of the compression force supported by each crutch.

56. As a protest against the umpire’s calls, a baseball pitcher throws a ball straight up into the air at a speed of 20.0 m/s. In the process, he moves his hand through a distance of 1.50 m. If the ball has a mass of 0.150 kg, find the force he exerts on the ball to give it this upward speed.

57. Three objects are connected on a table as shown in Figure P4.57. The rough table has a coefficient of kinetic friction of 0.350. The objects have masses of 4.00 kg, 1.00 kg, and 2.00 kg as shown, and the pulleys are frictionless. (a) Draw a free-body diagram for each object. (b) Determine the acceleration of each object and each object’s directions. (c) Determine the tensions in the two cords. (d) If the tabletop were smooth, would the tensions increase, decrease, or remain the same? Explain.

58. The force exerted by the wind on a sailboat is approximately perpendicular to the sail and proportional to the component of the wind velocity perpendicular to the sail. For the 800-kg sailboat shown in Figure P4.58, the proportionality constant is

$$F_{\text{wind}} = \left(550 \frac{\text{N}}{\text{m/s}}\right)v_{\text{wind}}.$$  

Water exerts a force along the keel (bottom) of the boat that prevents it from moving sideways, as shown in the
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63. A box rests on the back of a truck. The coefficient of static friction between the box and the bed of the truck is 0.300. (a) When the truck accelerates forward, what force accelerates the box? (b) Find the maximum acceleration the truck can have before the box slides.

64. Three objects are connected by light strings as shown in Figure P4.64. The string connecting the 4.00-kg object and the 5.00-kg object passes over a light frictionless pulley. Determine (a) the acceleration of each object and (b) the tension in the two strings.

65. A frictionless plane is 10.0 m long and inclined at 35.0°. A sled starts at the bottom with an initial speed of 5.00 m/s up the incline. When the sled reaches the point at which it momentarily stops, a second sled is released from the top of the incline at the same moment. (a) Determine the distance that the first sled traveled up the incline. (b) Determine the initial speed of the second sled.

66. A high diver of mass 70.0 kg jumps off a board 10.0 m above the water. If her downward motion is stopped 2.00 s after she enters the water, what average upward force did the water exert on her?

67. A 2.00-kg aluminum block and a 6.00-kg copper block are connected by a light string over a frictionless pulley. The two blocks are allowed to move on a fixed steel block wedge (of angle $\theta = 30.0^\circ$) as shown in Figure P4.67. Making use of Table 4.2, determine (a) the acceleration of the two blocks and (b) the tension in the string.

68. A 3.0-kg object hangs at one end of a rope that is attached to a support on a railroad car. When the car accelerates to the right, the rope makes an angle of 4.0° with the vertical, as shown in Figure P4.68. Find the acceleration of the car.
69. Two boxes of fruit on a frictionless horizontal surface are connected by a light string as in Figure P4.69, where \( m_1 = 10 \text{ kg} \) and \( m_2 = 20 \text{ kg} \). A force of 50 N is applied to the 20-kg box. (a) Determine the acceleration of each box and the tension in the string. (b) Repeat the problem for the case where the coefficient of kinetic friction between each box and the surface is 0.10.

70. Measuring coefficients of friction A coin is placed near one edge of a book lying on a table, and that edge of the book is lifted until the coin just slips down the incline as shown in Figure P4.70. The angle of the incline, \( \theta_c \), called the critical angle, is measured. (a) Draw a free-body diagram for the coin when it is on the verge of slipping and identify all forces acting on it. Your free-body diagram should include a force of static friction acting up the incline. (b) Is the magnitude of the friction force equal to \( \mu SS \) for angles less than \( \theta_c \)? Explain. What can you definitely say about the magnitude of the friction force for any angle \( \theta \leq \theta_c \)? (c) Show that the coefficient of static friction is given by \( \mu S = \tan \theta_c \). (d) Once the coin starts to slide down the incline, the angle can be adjusted to a new value \( \theta_s \leq \theta_c \) such that the coins moves down the incline with constant speed. How does observation enable you to obtain the coefficient of kinetic friction?

71. A fisherman poles a boat as he searches for his next catch. He pushes parallel to the length of the light pole, exerting a force of 240 N on the bottom of a shallow lake. The pole lies in the vertical plane containing the boat’s keel. At one moment, the pole makes an angle of 35.0° with the vertical and the water exerts a horizontal drag force of 47.5 N on the boat, opposite to its forward velocity of magnitude 0.857 m/s. The mass of the boat including its cargo and the worker is 370 kg. (a) The water exerts a buoyant force vertically upward on the boat. Find the magnitude of this force. (b) Assume the forces are constant over a short interval of time. Find the velocity of the boat 0.450 s after the moment described. (c) If the angle of the pole with respect to the vertical increased but the exerted force against the bottom remained the same, what would happen to buoyant force and the acceleration of the boat?

72. A rope with mass \( m_r \) is attached to a block with mass \( m_b \) as in Figure P4.72. Both the rope and the block rest on a horizontal, frictionless surface. The rope does not stretch. The free end of the rope is pulled to the right with a horizontal force \( F \). (a) Draw free-body diagrams for the rope and the block, noting that the tension in the rope is not uniform. (b) Find the acceleration of the system in terms of \( m_r, m_b, \) and \( F \). (c) Find the magnitude of the force the rope exerts on the block. (d) What happens to the force on the block as the rope’s mass approaches zero? What can you state about the tension in a light cord joining a pair of moving objects?

73. A van accelerates down a hill (Fig. P4.73), going from rest to 30.0 m/s in 6.00 s. During the acceleration, a toy \((m = 0.100 \text{ kg})\) hangs by a string from the van’s ceiling. The acceleration is such that the string remains perpendicular to the ceiling. Determine (a) the angle \( \theta \) and (b) the tension in the string.

74. An inquisitive physics student, wishing to combine pleasure with scientific inquiry, rides on a roller coaster sitting on a bathroom scale. (Do not try this yourself on a roller coaster that forbids loose, heavy packages.) The bottom of the seat in the roller-coaster car is in a plane parallel to the track. The seat has a perpendicular back and a seat belt that fits around the student’s chest in a plane parallel to the bottom of the seat. The student lifts his feet from the floor so that the scale reads his weight, 200 lb, when the car is horizontal. At one point during the ride, the car zooms with negligible friction down a straight slope inclined at 30.0° below the horizontal. What does the scale read at that point?
75. The parachute on a race car of weight 8820 N opens at the end of a quarter-mile run when the car is traveling at 35 m/s. What total retarding force must be supplied by the parachute to stop the car in a distance of 1000 m?

76. On an airplane’s takeoff, the combined action of the air around the engines and wings of an airplane exerts an 8000-N force on the plane, directed upward at an angle of 65.0° above the horizontal. The plane rises with constant velocity in the vertical direction while continuing to accelerate in the horizontal direction. (a) What is the weight of the plane? (b) What is its horizontal acceleration?

77. The board sandwiched between two other boards in Figure P4.77 weighs 95.5 N. If the coefficient of friction between the boards is 0.663, what must be the magnitude of the compression forces (assumed to be horizontal) acting on both sides of the center board to keep it from slipping?

78. A sled weighing 60.0 N is pulled horizontally across snow so that the coefficient of kinetic friction between sled and snow is 0.100. A penguin weighing 70.0 N rides on the sled, as in Figure P4.78. If the coefficient of static friction between penguin and sled is 0.700, find the maximum horizontal force that can be exerted on the sled before the penguin begins to slide off.

79. A 72-kg man stands on a spring scale in an elevator. Starting from rest, the elevator ascends, attaining its maximum speed of 1.2 m/s in 0.80 s. The elevator travels with this constant speed for 5.0 s, undergoes a uniform negative acceleration for 1.5 s, and then comes to rest. What does the spring scale register (a) before the elevator starts to move? (b) During the first 0.80s of the elevator’s ascent? (c) While the elevator is traveling at constant speed? (d) During the elevator’s negative acceleration?

80. A magician pulls a tablecloth from under a 200-g mug located 30.0 cm from the edge of the cloth. The cloth exerts a friction force of 0.100 N on the mug and is pulled with a constant acceleration of 3.00 m/s². How far does the mug move relative to the horizontal tabletop before the cloth is completely out from under it? Note that the cloth must move more than 30 cm relative to the tabletop during the process.

81. An inventive child wants to reach an apple in a tree without climbing the tree. Sitting in a chair connected to a rope that passes over a frictionless pulley (Fig. P4.81), the child pulls on the loose end of the rope with such a force that the spring scale reads 250 N. The child’s true weight is 320 N, and the chair weighs 160 N. (a) Show that the acceleration of the system is upward and find its magnitude. (b) Find the force the child exerts on the chair.

82. A fire helicopter carries a 620-kg bucket of water at the end of a 20.0-m-long cable. Flying back from a fire at a constant speed of 40.0 m/s, the cable makes an angle of 40.0° with respect to the vertical. Determine the force exerted by air resistance on the bucket.