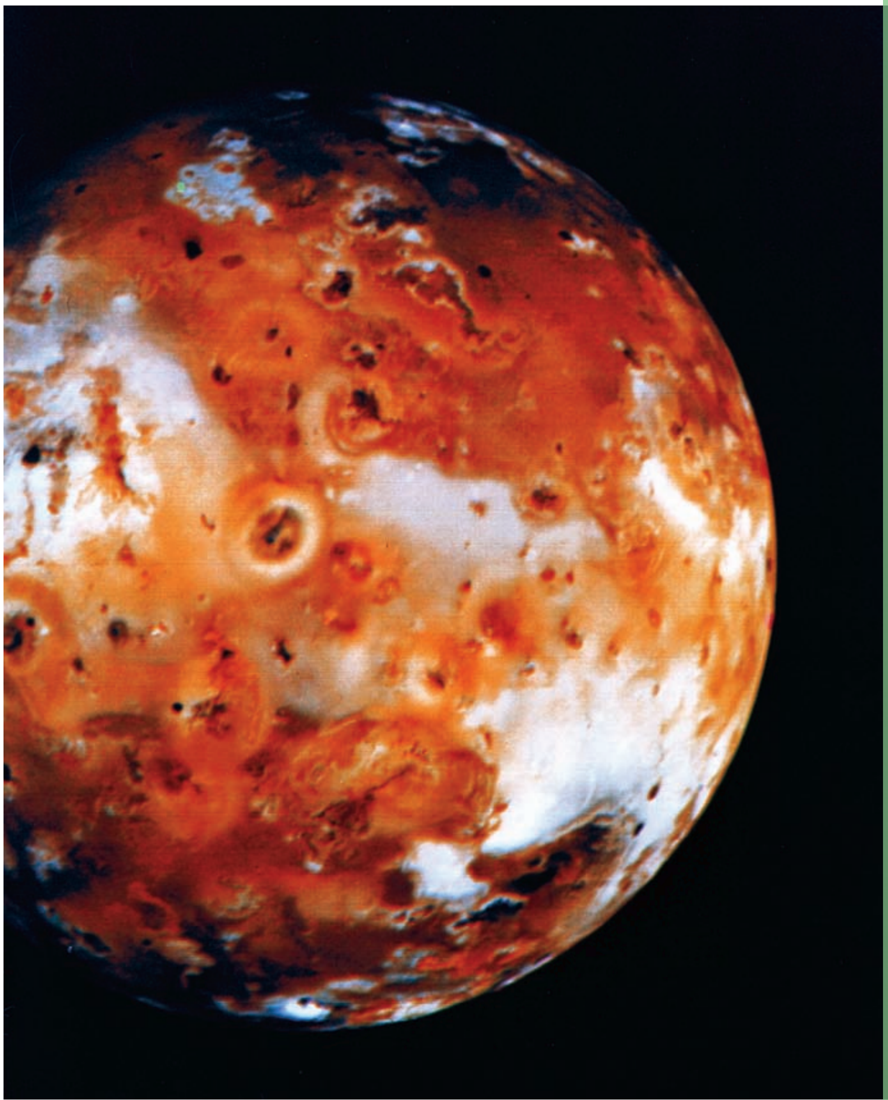
CHAPTER 2

# Force



Io, one of the moons of Jupiter, as photographed by *Voyager* 1 from a distance of 862 000 km.

The *Voyager* 1 and *Voyager* 2 space probes were launched in 1977. Between them, they explored all the large planets of the outer solar system (Jupiter, Saturn, Uranus, and Neptune) and 48 of their moons. *Voyager* 1 showed that rings of Saturn are made up of thousands of "ringlets" made up of particles of ice and rock. *Voyager* 2 photographed the extreme geography of Miranda, a moon of Uranus, showing a 6-km cliff on a moon that is only a few hundred kilometers in size. Passing only 5000 km from Neptune, *Voyager* 2 discovered that the planet is buffeted by 2000 km/h winds.

More than 30 years after being launched, *Voyager* 1 is now exploring the outer reaches of the solar system more than 17 billion kilometers from the Sun—more than 100 times as far as Earth—and *Voyager* 2 is more than 14 billion kilometers from the Sun. They are heading out of the solar system at speeds of 17 km/s and 16 km/s, respectively, without being propelled by rockets or any other kind of engine. How can they continue to move at such high speeds for many years without an engine to drive them? (See p. 37 for the answer.)

## BIOMEDICAL APPLICATIONS

- Tensile forces in the body (Sec. 2.8; Ex. 2.3; Probs. 32, 106, 115, 116, 129, 130)
- Traction apparatus (Ex. 2.4; Prob. 114)
- Newton's third law: swimming, walking, skiing (Sec. 2.5)

**Concepts & Skills to Review**

- scientific notation and significant figures (Section 1.4)
- converting units (Section 1.5)
- Pythagorean theorem (Appendix A.6)
- trigonometric functions: sine, cosine, and tangent (Appendix A.7)
- problem-solving techniques (Section 1.7)
- meanings of *velocity* and *mass* in physics (Section 1.2)

## 2.1 INTERACTIONS AND FORCES

This chapter begins our study of **mechanics,** the branch of physics that considers how interactions between objects affect the motion of those objects. Just as human life would be dull without social interactions, the physical universe would be dull without physical interactions. Social interactions with friends and family change our behavior; physical interactions change the "behavior" (motion, temperature, etc.) of matter.

An interaction between two objects can be described and measured in terms of two *forces,* one exerted on each of the two interacting objects. A **force** is a push or a pull. When you play soccer, your foot exerts a force on the ball while the two are in contact, thereby changing the speed and direction of the ball's motion. At the same time, the ball exerts a force on your foot, the effect of which you can feel. To understand the motion of an object, whether it be a soccer ball or the International Space Station, we need to analyze the forces acting on the object.

**CONNECTION:**

Newton's third law (Sec. 2.5) tells us not only that forces always come in *interaction pairs* but also how the magnitudes and directions of the forces are related.

To correctly identify forces, you should be able to describe them as *(type of force)* exerted on *(object)* by *(object).* For example: contact force exerted on the ball by the foot; gravitational force exerted on the Space Station by Earth.

**Long-range Forces** Forces exerted on macroscopic objects—objects that are large enough for us to observe without instrumentation—can be either long-range forces or contact forces. **Long-range forces** do not require the two objects to be touching. These forces can exist even if the two objects are far apart and even if there are other objects between the two. For example, gravity is a long-range force. The gravitational force exerted on the Earth by the Sun keeps the Earth in orbit around the Sun, despite the great distance between them and despite other planets that occasionally come between them. The Earth also exerts a long-range gravitational force on objects on or near its surface. We call the size of the gravitational force (also called the strength, or **magnitude,** of the force) that a planet or moon exerts on a nearby object the object's **weight.**

Part 3 of this book treats electromagnetic forces in detail. Until then, you can safely assume that gravity is the only significant long-range interaction unless the statement of a problem indicates otherwise.

**EVERYDAY PHYSICS DEMO**

Besides gravity, other long-range forces are electric or magnetic in nature. On a dry day, run a plastic comb vigorously through your hair or rub it on a wool sweater until you hear some crackling. Now hold the comb close to small pieces of a torn paper napkin. Observe the long-range electrical interaction between the paper and the comb.

Now take a refrigerator magnet. Hold it near but not touching the refrigerator door or another magnet. You can feel the effect of a long-range magnetic interaction.

A soccer player's foot exerts a force on the ball only when they are touching. The ball also exerts a force on the foot, but only while they touch. Once the ball loses contact with the foot, the only forces acting on it are a long-range gravitational force due to the Earth and a contact force due to the air.

**Contact Forces** All forces exerted on macroscopic objects, other than long-range gravitational and electromagnetic forces, involve contact. **Contact forces** exist only as long as the objects are touching one another. Your foot has no noticeable effect on a soccer ball's motion until the two come into contact, and the force lasts only as long as they are in contact. Once the ball moves away from your foot, your foot has no further influence over the ball's motion.

The idea of contact is a useful simplification for macroscopic objects. What we call a single contact force is really the net effect of enormous numbers of electromagnetic forces between atoms on the surfaces of the two objects. On an atomic scale, the idea of "contact" breaks down. There is no way to define "contact" between two atoms—in other words, there is no unique distance between the atoms at which the forces they exert on each other suddenly become zero.

### CHECKPOINT 2.1

Identify the forces acting on the soccer player in the photo. Describe each as *(type of force)* exerted on the player by *(object)*.

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## Measuring Forces

If the concept of force is to be useful in physics, there must be a way to measure forces. Consider a simple spring scale (Fig. 2.1). As the scale's pan is pulled down, a spring is stretched. The harder you pull, the more the spring stretches. As the spring stretches, an attached pointer moves. Then all we have to do to measure the applied force is to calibrate the scale so the amount of stretch measures the magnitude of the force.

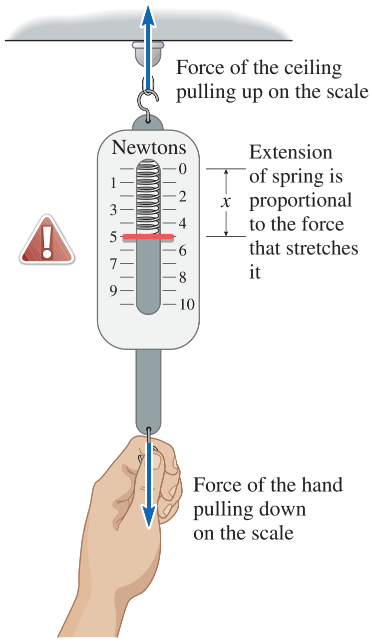


**Figure 2.1** As the bottom of a spring scale is pulled downward, the spring stretches. We can measure the force by measuring the extension of the spring. For many springs, the extension is approximately proportional to the force, which makes calibration easy. Note that there is a pull on *both* ends of the scale. The ceiling pulls up on the scale and supports the scale from above. (Bathroom scales are similar, but they measure the *compression* of a spring.)

In the United States, supermarket scales are generally calibrated to measure forces in pounds (lb). In the SI system, the unit of force is the **newton** (N). To convert pounds to newtons, use the approximate conversion factors

$$1\ \text{lb} = 4.448\ \text{N} \quad \text{or} \quad 1\ \text{N} = 0.2248\ \text{lb} \tag{2-1}$$

There are more sophisticated means for measuring forces than a supermarket scale. Even so, many operate on the same principle as the supermarket scale: a force is measured by the deformation—change of size or shape—it produces in some object.

## Force Is a Vector Quantity

The magnitude of a force is *not* a complete description of the force. The *direction* of the force is equally important. The direction of the brief contact force exerted by a soccer player's foot on the ball can make the difference between scoring a goal or not.

Force is one of many quantities in physics that are called **vectors.** All vectors have a direction in space as well as a magnitude. Section 1.2 mentioned that velocity, as defined in physics, has magnitude and direction. Velocity is another vector quantity: the magnitude of the velocity vector is the speed at which the object moves, and the direction of the velocity vector is the direction of motion.

**CONNECTION:**

Other vector quantities you will study in this book include position, displacement, acceleration, momentum, angular momentum, torque, and the electric and magnetic fields. All these quantities have both magnitude and direction. The mathematics of adding vectors and finding their components that we learn in this chapter are the same for *any* vector.

The direction of any vector is always a *physical direction in space* such as up, down, north, or 35° south of west. If a homework or exam question has you calculate a vector quantity such as force or velocity, don't forget to specify the direction as well as the magnitude in your answer. One without the other is incomplete.

**Scalars and Vectors** Mass is an example of a quantity that is a **scalar** rather than a vector. A scalar quantity can have magnitude, algebraic sign (positive or negative), and units, but not a direction in space. When scalars are added or subtracted, they do so in the usual way: 3 kg of water plus 2 kg of water is always equal to 5 kg of water. Adding vectors is different. All vectors follow the same rules of addition—rules that take into account the directions of the vectors being added. A 300-N force added to a 200-N force gives different results, depending on the directions of the two forces. If two friends are trying to push a car out of a snowbank, they help each other by applying forces *in the same direction* so the sum of the two forces is as large as possible. If they push in *opposite* directions, the net effect of the two forces would be *much* smaller. Whenever you need to add or subtract quantities, check whether they are vectors. If so, be sure to add or subtract them correctly according to the methods you will learn in Sections 2.2 and 2.3. *Do not just add their magnitudes.* A plus sign (+) between vector quantities indicates *vector addition,* not ordinary addition. An equals sign (=) between vector quantities means that the vectors are identical in magnitude *and* direction, *not* simply that their magnitudes are equal.

In this book, an arrow over a boldface symbol indicates a vector quantity ($\vec{\mathbf{F}}$). (Some books use boldface without the arrow or the arrow without boldface.) When writing by hand, always draw an arrow over a vector symbol to distinguish it from a scalar. When the symbol for a vector is written without the arrow and in italics rather than boldface ($F$), it stands for the *magnitude* of the vector (which is a scalar). Absolute value bars are also used to stand for the magnitude of a vector, so $F = |\vec{\mathbf{F}}|$. The magnitude of a vector may have units and is never negative; it can be positive or zero.

## Conceptual Example 2.1

### Body Temperature

Normal body temperature is 37°C. An adult with the flu might have a body temperature of around 39°C. Is temperature a vector quantity or a scalar quantity?

**Strategy** If a quantity is a vector, it must have both a magnitude and a physical direction in space.

**Solution and Discussion** Does temperature have a direction? A temperature in Fahrenheit (°F) or Celsius (°C) can be above or below zero—is that a direction? No. A vector must have a *physical direction in space.* It does not make sense to say that the body temperature of a patient is "38.4°C in the southwest direction." "The patient's temperature is up 1.4°C today," means that it has increased, not that it is pointing vertically upward. Temperature is a scalar. If we need to subtract temperatures to find the change in temperature, we subtract them like ordinary numbers. If the patient's temperature changes from 38.4°C to 37.7°C, the temperature change is

$$\Delta T = T_{\text{final}} - T_{\text{initial}} = 37.7°\text{C} - 38.4°\text{C} = -0.7°\text{C}$$

**Conceptual Practice Problem 2.1** Bank Balance

When you deposit a paycheck, the balance of your checking account "goes up." When you pay a bill, it "goes down." Is the balance of your account a vector quantity?

## 2.2 GRAPHICAL VECTOR ADDITION

To add two forces graphically, first draw an arrow to represent one of them (Fig. 2.2a). (It does not matter in what order vectors are added; $\vec{\mathbf{F}}_1 + \vec{\mathbf{F}}_2 = \vec{\mathbf{F}}_2 + \vec{\mathbf{F}}_1$.) The arrow points in the direction of the force, and its length is proportional to the magnitude of the vector. It doesn't matter where you start drawing the arrow. The value of a vector is not changed by moving it as long as its direction and magnitude are not changed.

Now draw the second force arrow starting where the first ends. In other words, place the "tail" of the second arrow at the "tip" of the first (Fig 2.2b). Finally, draw an arrow starting from the *tail* of the first and ending at the *tip* of the second. This arrow represents the vector sum of the two forces (Fig 2.2c). A common error is to draw the sum from the tip of the second to the tail of the first (Fig. 2.2d). If the lengths and directions of the vectors are drawn accurately to scale, using a ruler and a protractor, then the length and direction of the sum can be determined with the ruler and protractor. To add more than two forces, continue drawing them tip to tail.

Adding vectors along the same line, we can draw these conclusions:

- If two forces are in the same direction, their sum is in the same direction (Fig. 2.3a) and its magnitude is the sum of the magnitudes of the two. If you and your friend

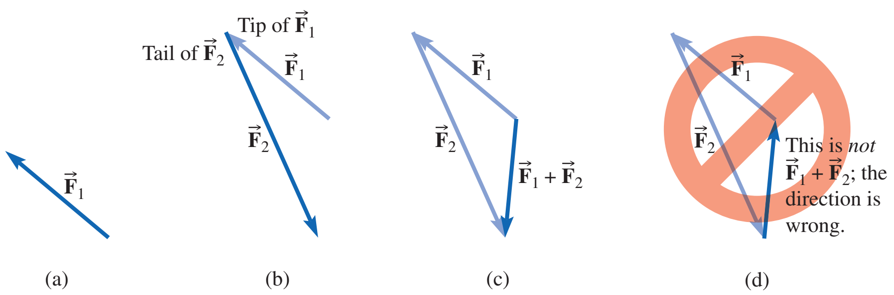


**Figure 2.2** Adding two force vectors graphically. (a) Draw one vector arrow. (b) Draw the second, starting where the first arrow ended. (c) The sum of the two is represented by an arrow drawn from the start of the first to the end of the second. (d) Be careful to avoid this common mistake.

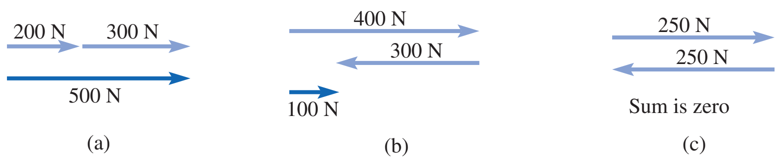


**Figure 2.3** Addition of vectors that are (a) in the same direction and (b) in opposite directions. (c) The sum of two vectors with equal magnitudes and opposite directions is zero. (When adding vectors whose directions are opposite, it sometimes helps to draw them next to each other rather than on top of each other so the vectors and their sum can be clearly seen.)

push a heavy trunk with forces of 200 N and 300 N in the same direction, the net effect is that of a 500-N force in that direction.

- If two forces are in opposite directions, the magnitude of their sum is the *difference* between the magnitudes of the two vectors (Fig. 2.3b)—the larger minus the smaller, since vector magnitudes are never negative. The direction of the vector sum is the direction of the larger of the two. Pushing that trunk with a 400-N force to the right and a 300-N force to the left has the net effect of a 100-N force to the right.
- The only way that two vectors can add to zero is if they are opposites: they must have the same magnitude but opposite directions (Fig. 2.3c).

## CHECKPOINT 2.2

What is the vector sum of a force of 20 N directed north and a force of 50 N directed south?

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## Example 2.2

### Bringing Home the Maple Syrup

Two draft horses, Sam and Bob, are dragging a sled loaded with jugs of maple syrup. They pull with horizontal forces of equal magnitude 1.50 kN on the front of the sled. The force due to Sam is in the direction 15° north of east, and the force due to Bob is 15° south of east (Fig. 2.4). Use the graphical method of vector addition to find the magnitude and direction of the sum of the forces exerted on the sled by the two horses.

**Strategy** Forces are vector quantities. To add vectors graphically and get an accurate result, we will use a ruler and a protractor. The protractor is used to draw the vector arrows in the correct directions and the ruler is used to draw them with the correct lengths. We must choose a convenient scale for the lengths of the vector arrows. Here we choose to represent 200 N as a length of

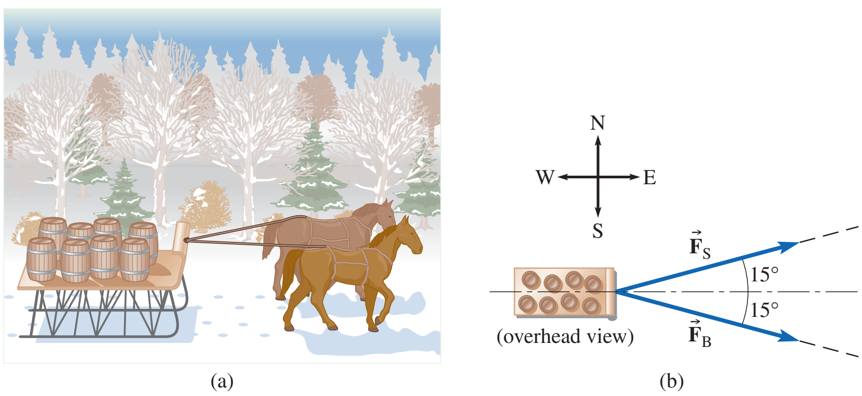



**Figure 2.4**
(a) Hauling the maple syrup (side view). (b) Forces exerted by Sam and Bob on the sled (overhead view).

*continued on next page*

Example 2.2 continued

1 cm, so the 1.50-kN forces are drawn as vector arrows of length

$$1.50\ \text{kN} \times \frac{1000\ \text{N}}{1\ \text{kN}} \times \frac{1\ \text{cm}}{200\ \text{N}} = 7.50\ \text{cm}$$

Once the sum is drawn, its direction and magnitude are determined with the ruler and protractor.

**Solution** We can redraw any vector starting at any point, as long as we do not change its direction or magnitude. We can either add vector $\vec{\mathbf{F}}_B$ (the force exerted by Bob) to vector $\vec{\mathbf{F}}_S$ (the force exerted by Sam) or add vector $\vec{\mathbf{F}}_S$ to vector $\vec{\mathbf{F}}_B$. Both possibilities are shown in Fig. 2.5.

The drawing shows that the direction of the sum is due east. Measurement of the length of the arrow that represents the vector sum arrow yields 14.5 cm. The magnitude of the sum is, therefore,

$$14.5\ \text{cm} \times \frac{200\ \text{N}}{1\ \text{cm}} \times \frac{1\ \text{kN}}{1000\ \text{N}} = 2.90\ \text{kN}$$

The sum of the two forces is 2.90 kN due east.

**Discussion** It makes sense that the sum of the two forces points east since they are equal in magnitude and pull at equal angles on either side of east.

A quick check on the magnitude of the sum: if the two vectors being added were parallel, their sum would have magnitude 3.00 kN. Since they are not parallel, their sum must have a magnitude *smaller* than 3.00 kN. The magnitude of $\vec{\mathbf{F}}_S + \vec{\mathbf{F}}_B$ is only *slightly* smaller than if they were in the same direction because the angle between the two vectors is relatively small.

**Practice Problem 2.2** Pulling at Other Angles

(a) If Sam and Bob were to pull with forces of the same magnitude as before (1.50 kN) but angled at 30° north and south of east, respectively, instead of 15°, would the sum of the two be larger, smaller, or the same magnitude as before? Illustrate with a sketch. (b) If Sam pulls at 10° north of east while Bob pulls at 15° south of east, is it still possible for the sum of the two forces to be due east if their magnitudes are not the same? Which force must have the larger magnitude? Illustrate with a sketch.

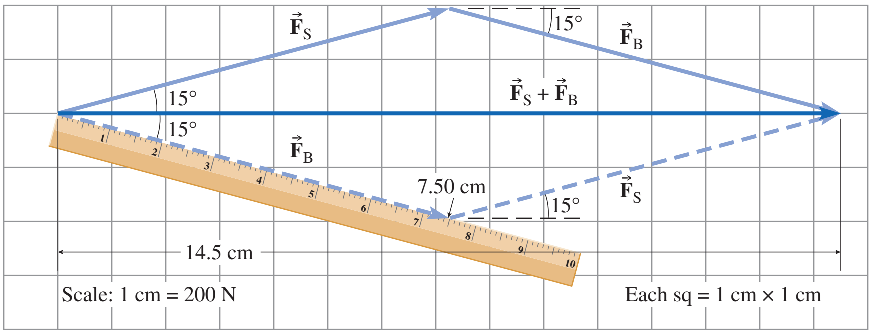



**Figure 2.5**

Graphical addition of the two force vectors. The tail of the second vector is placed at the tip of the first. The sum is the vector from the tail of the first to the tip of the second. Adding the vectors in a different order gives the same result.

## 2.3 VECTOR ADDITION USING COMPONENTS

### Components of a Vector

Any vector can be expressed as the sum of vectors parallel to the *x*-, *y*-, and (if needed) *z*-axes. The *x*-, *y*-, and *z*-**components** of a vector indicate the magnitude and direction of the three vectors along the axes. A component has magnitude, units, and an algebraic sign (+ or −). The sign of a component indicates the direction along that axis. A positive *x*-component indicates the direction of the positive *x*-axis, but a negative *x*-component indicates the opposite direction (the negative *x*-axis). A vector quantity can be specified either by giving its magnitude and direction or by giving its components; the two representations are equally acceptable. The *x*-, *y*-, and *z*-components of vector $\vec{\mathbf{A}}$ are written with subscripts as follows: $A_x$, $A_y$, and $A_z$. The process of finding the components of a vector is called **resolving** the vector into its components. Before resolving a vector into components, we must choose a coordinate system (the directions of the *x*- and *y*-axes).

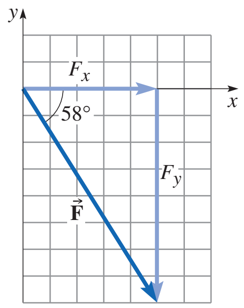
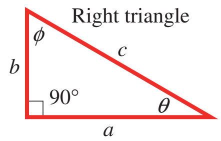



**Figure 2.6** Resolving a force vector $\vec{\mathbf{F}}$ into *x*- and *y*-components by drawing a right triangle with the vector arrow as the hypotenuse and the sides parallel to the *x*- and *y*-axes.




$\phi = 90° - \theta$

$$\sin\theta = \frac{\text{side opposite } \angle\theta}{\text{hypotenuse}} = \frac{b}{c}$$

$$\cos\theta = \frac{\text{side adjacent } \angle\theta}{\text{hypotenuse}} = \frac{a}{c}$$

$$\tan\theta = \frac{\text{side opposite } \angle\theta}{\text{side adjacent } \angle\theta} = \frac{b}{a}$$

**Figure 2.7** Review of the trigonometric functions (see Appendix A.7 for more information).

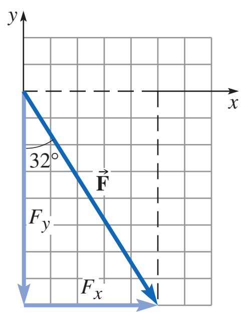



**Figure 2.8** Resolving the force vector into components using a different right triangle. Note that the vector arrow is still the hypotenuse and the sides are still parallel to the *x*- and *y*-axes.

**Finding Components** Consider a force vector $\vec{\mathbf{F}}$ that has magnitude 9.4 N and is directed 58° below the +*x*-axis (Fig. 2.6). We can think of $\vec{\mathbf{F}}$ as the sum of two vectors, one parallel to the *x*-axis and the other parallel to the *y*-axis. The magnitudes of these two vectors are the *magnitudes* (absolute values) of the *x*- and *y*-components of $\vec{\mathbf{F}}$. We can find the magnitudes of the components using the right triangle in Fig. 2.6 and the trigonometric functions in Fig. 2.7. The length of the arrow represents the magnitude of the force ($F = 9.4$ N), so

$$\cos 58° = \frac{\text{adjacent}}{\text{hypotenuse}} = \frac{|F_x|}{F} \quad \text{and} \quad \sin 58° = \frac{\text{opposite}}{\text{hypotenuse}} = \frac{|F_y|}{F}$$

Now we must determine the correct algebraic sign for each of the components. From Fig. 2.6, the vector along the *x*-axis points in the *positive x*-direction and the vector along the *y*-axis points in the *negative y*-direction, so in this case,

$$F_x = +F\cos 58° = 5.0\text{ N} \quad \text{and} \quad F_y = -F\sin 58° = -8.0\text{ N}$$

Using the right triangle in Fig. 2.8 gives the same values for the *x*- and *y*-components of $\vec{\mathbf{F}}$ since cos 32° = sin 58° and sin 32° = cos 58°.

### Problem-Solving Strategy: Finding the *x*- and *y*-Components of a Vector from Its Magnitude and Direction

1. Draw a right triangle with the vector as the hypotenuse and the other two sides parallel to the *x*- and *y*-axes.
2. Determine one of the angles in the triangle.
3. Use trigonometric functions to find the magnitudes of the components. Make sure your calculator is in "degree mode" to evaluate trigonometric functions of angles in degrees and "radian mode" for angles in radians.
4. Determine the correct algebraic sign for each component.

Sometimes a vector is written as a list of its components in order, separated by a comma, inside parentheses. The force of Fig. 2.6 can be written: $\vec{\mathbf{F}} = (5.0\text{ N}, -8.0\text{ N})$.

**Finding Magnitude and Direction** We must also know how to reverse the process to find a vector's magnitude and direction from its components.

Suppose we knew the components of the force vector in Fig. 2.6, but not the magnitude and direction. Let us find the angle $\theta$ between $\vec{\mathbf{F}}$ and the +*x*-axis:

$$\theta = \tan^{-1}\frac{\text{opposite}}{\text{adjacent}} = \tan^{-1}\frac{|F_y|}{|F_x|} = \tan^{-1}\frac{8.0\text{ N}}{5.0\text{ N}} = 58°$$

From the Pythagorean theorem, the magnitude of $\vec{\mathbf{F}}$ is

$$F = \sqrt{F_x^2 + F_y^2} = \sqrt{(+5.0\text{ N})^2 + (-8.0\text{ N})^2} = 9.4\text{ N}$$

### Problem-Solving Strategy: Finding the Magnitude and Direction of a Vector from Its *x*- and *y*-Components

1. Sketch the vector on a set of *x*- and *y*-axes in the correct quadrant, according to the signs of the components.
2. Draw a right triangle with the vector as the hypotenuse and the other two sides parallel to the *x*- and *y*-axes.
3. In the right triangle, choose which of the unknown angles you want to determine.

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4. Use the inverse tangent function to find the angle. The lengths of the sides of the triangle represent $|F_x|$ and $|F_y|$. If $\theta$ is opposite the side parallel to the $x$-axis, then $\tan \theta = \text{opposite/adjacent} = |F_x/F_y|$. If $\theta$ is opposite the side parallel to the $y$-axis, then $\tan \theta = \text{opposite/adjacent} = |F_y/F_x|$. If your calculator is in "degree mode," then the result of the inverse tangent operation will be in degrees. [In general, the inverse tangent has *two* possible values between 0 and 360° because $\tan \alpha = \tan(\alpha + 180°)$. However, when the inverse tangent is used to find one of the angles in a right triangle, the result can never be greater than 90°, so the value the calculator returns is the one you want.]
5. Interpret the angle: specify whether it is the angle below the horizontal, or the angle west of south, or the angle clockwise from the negative $y$-axis, etc.
6. Use the Pythagorean theorem to find the magnitude of the vector.

$$F = \sqrt{F_x^2 + F_y^2} \qquad (2\text{-}2)$$

## Example 2.3

### Exercise Is Good for You

Suppose you are standing on the floor doing your daily exercises. For one exercise, you lift your arms up and out until they are horizontal. In this position, assume that the deltoid muscle exerts a force of 270 N at an angle of 15° above the horizontal on the humerus (Fig. 2.9). What are the $x$- and $y$-components of this force?

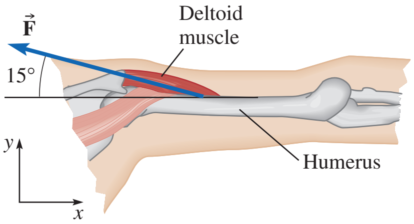



**Figure 2.9** Force exerted by the deltoid muscle on the humerus.

**Strategy** This problem gives the magnitude and direction of a force and asks for the components of the force. The directions of the axes are shown in Fig. 2.9. To find the components, we draw a right triangle with the force vector as the hypotenuse and the sides parallel to the $x$- and $y$-axes.

**Solution** Figure 2.10 shows a right triangle that can be used to find the components. The side of the triangle along the $x$-axis is adjacent to the 15° angle, so the cosine function is used for the $x$-component.

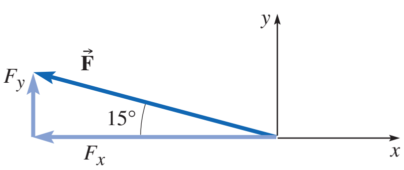



**Figure 2.10** Drawing a right triangle to find the force components. The vector arrow is the hypotenuse, and the two sides are parallel to the coordinate axes.

$$\cos 15° = \frac{\text{adjacent}}{\text{hypotenuse}} = \frac{|F_x|}{F}$$

The $x$-component is negative; the $+x$-axis points to the right, and the $x$-component of the force is to the left. Therefore,

$$F_x = -F\cos 15° = -270\text{ N} \times 0.9659 = -260\text{ N}$$

The sine function is used for the $y$-component since the side representing $F_y$ is opposite the 15° angle.

$$\sin 15° = \frac{\text{opposite}}{\text{hypotenuse}} = \frac{|F_y|}{F}$$

The $y$-component is up, along the $+y$-axis, so

$$F_y = +F\sin 15° = 270\text{ N} \times 0.2588 = 70\text{ N}$$

**Discussion** To check the answer, we can convert the components back into magnitude and direction.

$$F = \sqrt{(260\text{ N})^2 + (70\text{ N})^2} = 270\text{ N}$$

$$\theta = \tan^{-1}\left|\frac{F_y}{F_x}\right| = \tan^{-1}\frac{70\text{ N}}{260\text{ N}} = 15°$$

### Practice Problem 2.3 Tilling the Garden

While tilling your garden, you exert a force on the handles of the tiller that has components $F_x = +85$ N and $F_y = -132$ N. The $x$-axis is horizontal and the $y$-axis points up. What are the magnitude and direction of this force?

## Adding Vectors Using Components

Now that we know how to find components of vectors, we can use components to add vectors. Remember that each vector is thought of as the sum of vectors parallel to the axes (Fig. 2.11a). When adding vectors, we can add them in any order and group them as we please. So we can sum the $x$-components to find the $x$-component of the sum (Fig. 2.11b) and then do the same with the $y$-components (Fig. 2.11c):

$$\vec{\mathbf{C}} = \vec{\mathbf{A}} + \vec{\mathbf{B}} \quad \text{if and only if} \quad C_x = A_x + B_x \quad \text{and} \quad C_y = A_y + B_y \tag{2-3}$$

In Eq. (2-3), $A_x + B_x$ represents ordinary addition; the signs of the components carry the direction information.

### Problem-Solving Strategy: Adding Vectors Using Components

1. Find the $x$- and $y$-components of each vector to be added.
2. Add the $x$-components (*with their algebraic signs*) of the vectors to find the $x$-component of the sum. (If the signs are not correct, the sum will not be correct.)
3. Add the $y$-components (with their algebraic signs) of the vectors to find the $y$-component of the sum.
4. If necessary, use the $x$- and $y$-components of the sum to find the magnitude and direction of the sum.

**Unit Vector Notation** The same concept of vector components may be used to write vectors in a compact way. The **unit vectors** $\hat{\mathbf{x}}$ (read aloud as "x hat"), $\hat{\mathbf{y}}$, and $\hat{\mathbf{z}}$ are defined as vectors of magnitude 1 that point in the $+x$-, $+y$-, and $+z$-directions, respectively. (In some books, you may see them written as $\hat{\mathbf{i}}$, $\hat{\mathbf{j}}$, and $\hat{\mathbf{k}}$, respectively.) They are called *unit* vectors because the magnitude of each is the pure number 1—they do *not* have physical units such as kilograms or meters. Any vector $\vec{\mathbf{F}}$ can be written as the sum of three vectors along the coordinate axes:

$$\vec{\mathbf{F}} = F_x\hat{\mathbf{x}} + F_y\hat{\mathbf{y}} + F_z\hat{\mathbf{z}}$$

Here $F_x$ is the $x$-component of $\vec{\mathbf{F}}$, which has physical units and can be positive or negative. $F_x\hat{\mathbf{x}}$ is a vector of magnitude $|F_x|$ directed in the $+x$-direction if $F_x > 0$ and in the $-x$-direction if $F_x < 0$. For example, consider the force vector $\vec{\mathbf{F}}$ of Fig. 2.8. $\vec{\mathbf{F}}$ has $x$-component $F_x = +5.0$ N and $y$-component $F_y = -8.0$ N, so $\vec{\mathbf{F}} = (+5.0\text{ N})\hat{\mathbf{x}} + (-8.0\text{ N})\hat{\mathbf{y}}$.

Using unit vector notation is one way to keep track of vector components in vector addition and subtraction without writing separate equations for each component. Adding two vectors in the $xy$-plane looks like this:

$$\vec{\mathbf{F}}_1 + \vec{\mathbf{F}}_2 = \left(F_{1x}\hat{\mathbf{x}} + F_{1y}\hat{\mathbf{y}}\right) + \left(F_{2x}\hat{\mathbf{x}} + F_{2y}\hat{\mathbf{y}}\right)$$

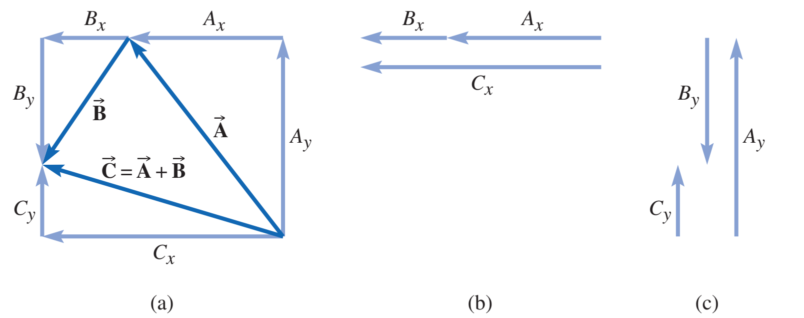



**Figure 2.11** (a) $\vec{\mathbf{C}} = \vec{\mathbf{A}} + \vec{\mathbf{B}}$, shown graphically with the $x$- and $y$-components of each vector illustrated. (b) $C_x = A_x + B_x$; (c) $C_y = A_y + B_y$. This illustrates the fact that vector addition can be done by components.

Regroping the terms shows that the $x$-component of the sum is the sum of the $x$-components and likewise for the $y$-components:

$$\vec{\mathbf{F}}_1 + \vec{\mathbf{F}}_2 = (F_{1x} + F_{2x})\hat{\mathbf{x}} + (F_{1y} + F_{2y})\hat{\mathbf{y}}$$

**Estimation Using Graphical Addition** Even when using the component method to add vectors, the graphical method is an important first step. A rough sketch of vector addition, even one made without carefully measuring the lengths or the angles, has important benefits. Sketching the vectors makes it much easier to get the signs of the components correct. The graphical addition also serves as a check on the answer—it provides an estimate of the magnitude and direction of the sum, which can be used to check the algebraic answer. Graphical addition gives you a mental picture of what is going on and an intuitive feel for the algebraic calculations.

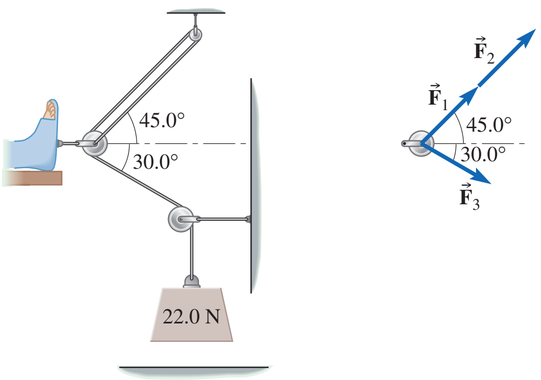
## Example 2.4

### Traction on a Foot

In a traction apparatus, three cords pull on the central pulley, each with magnitude 22.0 N, in the directions shown in Fig. 2.12. What is the sum of the forces exerted on the central pulley by the three cords? Give the magnitude and direction of the sum.

**Strategy** First, we sketch the graphical addition of the three forces to get an estimate of the magnitude and direction of the sum. Then, to get an accurate answer, we resolve the three forces into their $x$- and $y$-components, sum the components, and then calculate the magnitude and direction of the sum.

**Solution** Figure 2.13 shows the graphical addition of the three forces exerted on the central pulley by the cords. From this sketch, we can tell that the sum of the three forces is at a relatively small angle above the horizontal (roughly half of 45°) and has a magnitude a bit larger than 44 N.




(a) (b)

**Figure 2.12**
(a) A foot in traction; (b) the three forces exerted on the central pulley by the cords.

To find an algebraic solution, we find the components along the $x$- and $y$-axes and add them (Fig. 2.14). The $x$-components of the forces are

$$F_{1x} = F_{2x} = (22.0\ \text{N})\cos 45.0°$$

$$F_{3x} = (22.0\ \text{N})\cos 30.0°$$

The $y$-components of the forces are

$$F_{1y} = F_{2y} = (22.0\ \text{N})\sin 45.0°$$

$$F_{3y} = (-22.0\ \text{N})\sin 30.0°$$

The sum of the $x$-components is

$$F_x = F_{1x} + F_{2x} + F_{3x}$$

$$= 2 \times (22.0\ \text{N})\cos 45.0° + (22.0\ \text{N})\cos 30.0°$$

$$= 31.11\ \text{N} + 19.05\ \text{N} = 50.16\ \text{N}$$

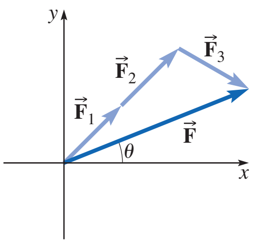
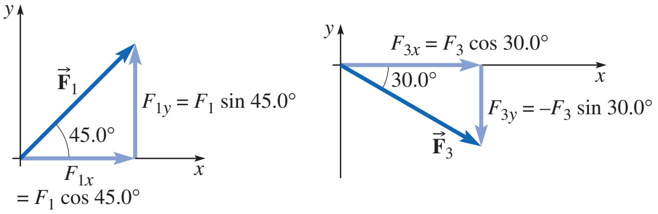



**Figure 2.13**
Graphical sum of the forces on the pulley due to the cords: $\vec{\mathbf{F}} = \vec{\mathbf{F}}_1 + \vec{\mathbf{F}}_2 + \vec{\mathbf{F}}_3$




(a) (b)

**Figure 2.14**
Using right triangles to find the components of (a) $\vec{\mathbf{F}}_1$ and (b) $\vec{\mathbf{F}}_3$. For clarity, the vector arrows are drawn twice as long as they were in Fig. 2.13.

*continued on next page*

### Example 2.4 continued

We keep an extra decimal place for now to minimize round-off error. The sum of the $y$-components is

$$F_y = F_{1y} + F_{2y} + F_{3y}$$
$$= 2 \times (22.0 \text{ N}) \sin 45.0° + (-22.0 \text{ N}) \sin 30.0°$$
$$= 31.11 \text{ N} - 11.00 \text{ N} = 20.11 \text{ N}$$

The magnitude of the sum is (Fig. 2.15):

$$F = \sqrt{F_x^2 + F_y^2} = \sqrt{(50.16 \text{ N})^2 + (20.11 \text{ N})^2} = 54.0 \text{ N}$$

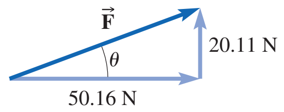



**Figure 2.15**
Finding the sum from its components. The magnitude is found using the Pythagorean theorem; the angle $\theta$ is found from the inverse tangent of opposite over adjacent.

and the direction of the sum is

$$\theta = \tan^{-1} \frac{\text{opposite}}{\text{adjacent}} = \tan^{-1} \frac{20.11 \text{ N}}{50.16 \text{ N}} = 21.8°$$

The sum of the forces exerted on the pulley by the three cords is 54.0 N at an angle 21.8° above the $+x$-axis.

**Discussion** To check the answer, look back at the graphical estimate. The magnitude of the sum (54.0 N) is somewhat larger than 44 N and the direction is at an angle very nearly half of 45° above the horizontal.

### Practice Problem 2.4 Changing the Pulley Angles

The pulleys are moved, after which $\vec{\mathbf{F}}_1$ and $\vec{\mathbf{F}}_2$ are at an angle of 30.0° above the $x$-axis and $\vec{\mathbf{F}}_3$ is 60.0° below the $x$-axis. (a) What is the sum of these three forces in component form? (b) What is the magnitude of the sum? (c) At what angle with the horizontal is the sum?

### CHECKPOINT 2.3

Sketch a vector arrow representing a force with $x$-component −6.0 N and $y$-component +2.0 N.

## 2.4 INERTIA AND EQUILIBRIUM: NEWTON'S FIRST LAW OF MOTION

### Introduction to Newton's Laws of Motion

In 1687, Isaac Newton (1643–1727) published one of the greatest scientific works of all time, his *Philosophiae Naturalis Principia Mathematica* (or *Principia* for short). The Latin title translates as *The Mathematical Principles of Natural Philosophy.* In the *Principia,* Newton stated three laws of motion that form the basis of classical mechanics. These laws describe how one or more forces acting on an object affect its motion and how the forces that interacting objects exert on one another are related.

Together with his law of universal gravitation, Newton's laws showed for the first time that the motion of the heavenly bodies (the Sun, the planets, and their satellites) and the motion of earthly bodies can be understood using the same physical principles. To pre-Newtonian thinkers, it seemed that there must be two different sets of physical laws: one set to describe the motion of the heavenly bodies, thought to be perfect and enduring, and another to describe the motion of earthly bodies that always come to rest.

**CONNECTION:**

In this chapter, we learn about a few kinds of forces. Later, when we learn about other forces, we always treat them the same: we add up *all* the forces acting on an object to find the net force.

### Net Force

When more than one force acts on an object, the subsequent motion of the object is determined by the *net force* acting on the object. The **net force** is the vector sum of *all* the forces acting on an object.

**Definition of net force:**
If $\vec{\mathbf{F}}_1, \vec{\mathbf{F}}_2, \ldots, \vec{\mathbf{F}}_n$ are *all* the forces acting on an object, then the net force $\vec{\mathbf{F}}_{net}$ acting on that object is the vector sum of those forces:

$$\vec{\mathbf{F}}_{net} = \sum \vec{\mathbf{F}} = \vec{\mathbf{F}}_1 + \vec{\mathbf{F}}_2 + \cdots + \vec{\mathbf{F}}_n \tag{2-4}$$

The symbol Σ is a capital Greek letter sigma that stands for "sum."

## CHECKPOINT 2.4

In Ex. 2.4, is the sum of the forces due to the three cords the *net* force on the central pulley?

---

## Newton's First Law of Motion

Newton's first law says that an object acted on by zero net force moves in a straight line with constant speed, or, if it is at rest, remains at rest. Using the concept of the velocity vector (see Sections 1.2 and 2.1), which is a measure of both the speed *and the direction of motion* of an object, we can restate the first law:

**CONNECTION:**

In Chapter 2 we concentrate on analyzing situations where the net force is zero. In Chapter 3, we will introduce Newton's second law, which lets us analyze cases when the net force is *not* zero.

### Newton's First Law of Motion

An object's velocity vector remains constant if and only if the net force acting on the object is zero.

This concise statement of Newton's first law includes both the case of an object at rest (zero velocity) and a moving object (nonzero velocity). Certainly it makes sense that an object at rest remains at rest unless some force acts on it to make it start to move. On the other hand, it may not be obvious that an object can continue to move without forces acting to keep it moving. In our experience, most moving objects come to rest because of forces that oppose motion, like friction and air resistance. A hockey puck can slide the entire length of a rink with very little change in speed or direction because the ice is slippery (frictional forces are small). If we could remove *all* the resistive forces, including friction and air resistance, the puck would slide without changing its speed or direction at all.

No force is required to keep an object in motion if there are no forces opposing its motion. When a hockey player strikes the puck with his stick, the brief contact force exerted on the puck by the stick changes the puck's velocity, but once the puck loses contact with the stick, it continues to slide along the ice even though the stick no longer exerts a force on it.

The *Voyager* space probes are so far from the Sun that the gravitational forces exerted on them due to the Sun are negligibly small. To a very good approximation, we can say that the net force acting on them is zero. Therefore, the probes continue moving at constant speed along a straight line. No applied force has to be maintained by an engine to keep them moving because there are no forces that oppose their motion.

Why *Voyager* space probes keep moving

**Inertia** Newton's first law is also called the **law of inertia.** In physics, **inertia** means resistance to *changes* in velocity. It does *not* mean resistance to the continuation of motion (or the tendency to come to rest). Newton based the law of inertia on the ideas of some of his predecessors, including Galileo Galilei (1564–1642) and René Descartes (1596–1650). In a series of clever experiments in which he rolled a ball up inclines of different angles, Galileo postulated that, if he could eliminate all resistive forces, a ball

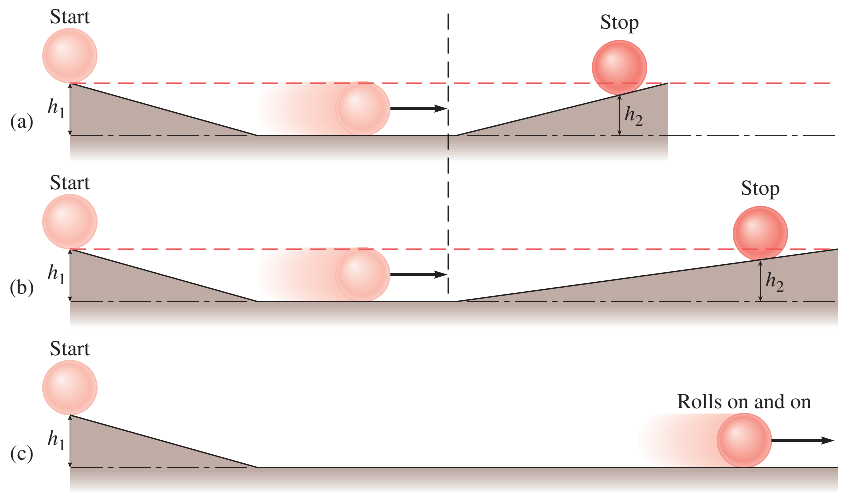



**Figure 2.16** (a) Galileo found that a ball rolled down an incline stops when it reaches *almost* the same height on the second incline. He decided that it would reach the *same* height if resistive forces could be eliminated. (b) As the second incline is made less and less steep, the ball rolls farther and farther before stopping. (c) If the second incline is horizontal and there are no resistive forces, the ball would never stop.

rolling on a horizontal surface would never stop (Fig. 2.16). Galileo made a brilliant conceptual leap from the real world with friction to an imagined, ideal world, free of friction. The law of inertia contradicted the view of the Greek philosopher Aristotle (384–322 B.C.E.). Almost 2000 years before Galileo, Aristotle had formulated his view that the natural state of an object is to be at rest; and, for an object to remain in motion, a force would have to act on it continuously. Galileo conjectured that, in the absence of friction and other resistive forces, an object in motion will continue to move even though no force is pushing or pulling it.

However, Galileo thought that the sustained motion of an object would be in a great circle around the Earth. Shortly after Galileo's death, Descartes argued that the motion of an object free of any forces should be along a straight line rather than a circle. Newton acknowledged his debt to Galileo, Descartes, and others when he wrote: "If I have seen farther, it is because I was standing on the shoulders of giants."

## Conceptual Example 2.5

### Snow Shoveling

The task of shoveling newly fallen snow from the driveway can be thought of as a struggle against the inertia of the snow. Without the application of a net force, the snow remains at rest on the ground. However, in an important way the inertia of the snow makes it *easier* to shovel. Explain.

**Strategy** Think about the physical motions used when shoveling snow. (If you live where there is no snow, think about shoveling gravel from a wheelbarrow to line a garden path.) For the shoveling to be facilitated by the snow's inertia, there must be a time when the snow is moving on its own, without the shovel pushing it.

**Solution and Discussion** Imagine scooping up a shovelful of snow and swinging the shovel forward toward the side of the driveway. The snow and the shovel are both in motion. Then suddenly the forward motion of the shovel stops, but the snow continues to move forward because of its inertia; it slides forward off the shovel, to be pulled down to the ground by gravity. The snow does not stop moving forward when the forward force due to the shovel is removed.

*continued on next page*

Conceptual Example 2.5 continued

This procedure works best with fairly dry snow. Wet sticky snow tends to cling to the shovel. The frictional force on the snow due to the shovel keeps it from moving forward and makes the job far more difficult. In this case, it might help to give the shovel a thin coating of cooking oil to reduce the frictional force the shovel exerts on the snow.

### Conceptual Practice Problem 2.5 Inertia on the Subway

Emma, a college student, stands on a subway car, holding on to an overhead strap. As the train starts to pull out of the station, she feels thrust toward the rear of the car; as the train comes to a stop at the next station, she feels thrust forward. Explain the role played by inertia in this situation.

### EVERYDAY PHYSICS DEMO

For an easy demonstration of inertia, place a quarter on top of an index card, or a credit card, balanced on top of a drinking glass (Fig. 2.17a). With your thumb and forefinger, flick the card so it flies out horizontally from under the quarter. What happens to the quarter? The horizontal force on the coin due to friction is small. With a negligibly small horizontal force, the coin tends to remain motionless while the card slides out from under it (Fig. 2.17b). Once the card is gone, gravity pulls the coin down into the glass (Fig. 2.17c).

## Free-Body Diagrams

An essential tool used to find the net force acting on an object is a **free-body diagram** (FBD): a simplified sketch of a single object with force vectors drawn to represent *every* force *acting on that object.* It must *not* include any forces that act on other objects. To draw a free-body diagram:

- Draw the object in a simplified way—you don't have to be Michelangelo to solve physics problems! Almost any object can be represented as a box or a circle, or even a dot.
- Identify all the forces that are exerted on the object. Take care not to omit any forces that are exerted on the object. Consider that everything touching the object may exert one or more contact forces. Then identify long-range forces (for now, just gravity unless electric or magnetic forces are specified in the problem).
- Check your list of forces to make sure that each force is exerted *on* the object of interest *by* some other object. Make sure you have not included any forces that are exerted *on other objects.*
- Draw vector arrows representing all the forces acting on the object. We usually draw the vectors as arrows that start on the object and point away from it. Draw the arrows so they correctly illustrate the directions of the forces. If you have enough information to do so, draw the lengths of the arrows so they are proportional to the magnitudes of the forces.

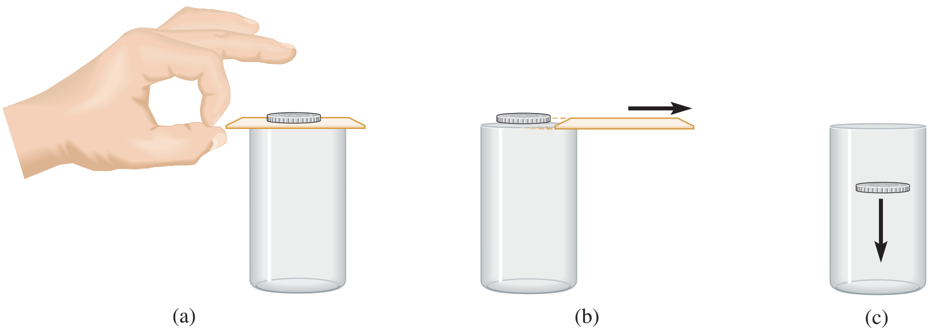



**Figure 2.17** A demonstration of inertia. A similar demonstration that you may have seen is pulling a tablecloth out from under a table setting, leaving all the dishes and glasses in place. (If you want to try this, please practice first with plastic dishes, not your grandmother's china.)

## An Object in Equilibrium Moves with Constant Velocity

When the net force acting on an object is zero, the object is said to be in **translational equilibrium:**

For an object in equilibrium,

$$\sum \vec{\mathbf{F}} = 0 \quad \text{(2-5a)}$$

*Equilibrium* conveys the idea that the forces are in balance; there is as much force upward as there is downward, as much to the right as to the left, and so forth. Any object with a constant velocity, whether at rest or moving in a straight line at constant speed, is in translational equilibrium. A vector can only have zero magnitude if all of its components are zero, so

For an object in equilibrium,

$$\sum F_x = 0 \quad \text{and} \quad \sum F_y = 0 \quad (\text{and} \quad \sum F_z = 0) \quad \text{(2-5b)}$$

**Application: Spring Scale** Using Newton's first law, we can now understand how a spring scale can be used to measure weight (the magnitude of the gravitational force exerted on an object). If a melon remains at rest in the pan of the scale, the net force on the melon must be zero. Only two forces are acting on the melon: gravity pulls down and the scale pulls up. Then these two forces must be equal in magnitude and opposite in direction. The scale measures the magnitude of the force it exerts on the melon, which is equal to the weight of the melon.

Example 2.6

### Hawk in Flight

A red-tailed hawk that weighs 8 N is gliding due north at constant speed. What is the total force acting on the hawk due to the air? Draw a free-body diagram for the hawk.

**Strategy** Since the hawk is gliding at constant velocity (constant speed *and* direction), it is in equilibrium—the net force acting on it is zero. We identify the forces acting on the hawk and determine what the force due to the air must be for the net force to be zero.

**Solution** Only two forces are acting on the hawk. One of them is long-range: the gravitational pull of the Earth ($\vec{\mathbf{F}}_{\text{grav}}$) whose magnitude is the bird's weight. The other is a contact force due to the air ($\vec{\mathbf{F}}_{\text{air}}$). Nothing else is in contact with the bird, so there are no other contact forces. Since the bird is in equilibrium, the net force acting on the bird must be zero:

$$\sum \vec{\mathbf{F}} = \vec{\mathbf{F}}_{\text{grav}} + \vec{\mathbf{F}}_{\text{air}} = 0$$

If two vectors add to zero, they must have the same magnitude and opposite directions. So the force on the bird due to the air is 8 N, directed upward. Figure 2.18 is the FBD for the hawk.

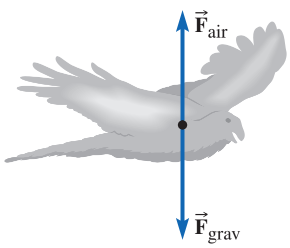



**Figure 2.18**
Free-body diagram for a hawk gliding with constant velocity. Two forces act on the hawk: a gravitational force and a contact force due to the air. Since the hawk's velocity is constant, these forces must add to zero.

**Discussion** The interaction between the hawk and the air is extremely complex at the microscopic level. The *net effect* of all the interactions between air molecules and the hawk produces an upward force of 8 N. (It is often convenient to think about different types of forces exerted by the air, such as lift, thrust, and drag. The vector sum of those forces is the total contact force due to the air.)

**Practice Problem 2.6** A Crate of Apples

An 80-N crate of apples sits at rest on the horizontal bed of a parked pickup truck. What is the force $\vec{\mathbf{C}}$ exerted on the crate by the bed of the pickup? Draw a free-body diagram for the crate.

## Choosing *x*- and *y*-Axes to Simplify Problem Solving

A problem can be made easier to solve with a good choice of axes. We can choose any direction we want for the *x*- and *y*-axes, as long as they are perpendicular to each other. Three common choices are

- *x*-axis horizontal and *y*-axis vertical, when the vectors all lie in a vertical plane;
- *x*-axis east and *y*-axis north, when the vectors all lie in a horizontal plane; and
- *x*-axis parallel to an inclined surface and *y*-axis perpendicular to it.

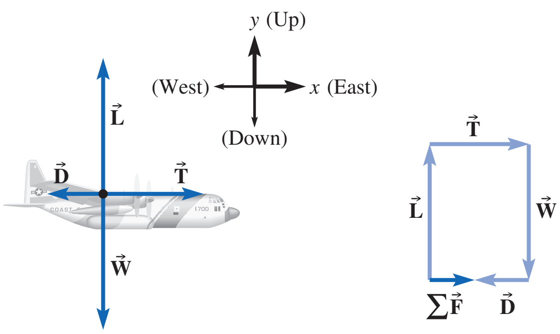
In an equilibrium problem, choose *x*- and *y*-axes so the fewest number of force vectors have both *x*- and *y*-components. It is always good practice to make a conscious *choice* of axes and then to draw them in the FBDs and any other sketches that you make in solving the problem.

## Example 2.7

### Net Force on an Airplane

The forces on an airplane in flight heading eastward are as follows: gravity = 16.0 kN, downward; lift = 16.0 kN, upward; thrust = 1.8 kN, east; and drag = 0.8 kN, west. (Lift, thrust, and drag are three forces that the air exerts on the plane.) What is the net force on the plane?

**Strategy** All the forces acting on the plane are given in the statement of the problem. After drawing these forces in the FBD for the plane, we add the forces to find the net force. To resolve the force vectors into components, we choose *x*- and *y*-axes pointing east and north, respectively. All four forces are then lined up with the axes, so each will have only one nonzero component, with a sign that indicates the direction along that axis. For example, the drag force points in the –*x*-direction, so its *x*-component is negative and its *y*-component is zero.




(a) (b)

**Figure 2.19**

(a) Free-body diagram for the airplane. (b) Graphical addition of the four force vectors yields the net force, $\Sigma\vec{\mathbf{F}}$.

**Solution** Figure 2.19a is the FBD for the plane, using $\vec{\mathbf{L}}$, $\vec{\mathbf{T}}$, and $\vec{\mathbf{D}}$ for the lift, thrust, and drag, respectively. $\vec{\mathbf{W}}$ stands for the gravitational force on the plane; its magnitude is the plane's weight *W*.

The sum of the *x*-components of the forces is

$$\sum F_x = L_x + T_x + W_x + D_x$$
$$= 0 + (1.8\text{ kN}) + 0 + (-0.8\text{ kN}) = 1.0\text{ kN}$$

The sum of the *y*-components of the forces is

$$\sum F_y = L_y + T_y + W_y + D_y$$
$$= (16\text{ kN}) + 0 + (-16\text{ kN}) + 0 = 0$$

The net force is 1.0 kN east.

**Discussion** A graphical check of the vector addition is a good idea. Figure 2.19b shows that the sum of the four forces is indeed in the +*x*-direction (east).

The net force on the airplane is *not* zero, so the airplane's velocity is not constant. To find out how the airplane's velocity changes, we would use Newton's second law of motion, which is the main topic of Chapter 3. Newton's second law relates the net force on an object to the rate of change of its velocity vector.

### Practice Problem 2.7 New Forces on the Airplane

Find the net force on the airplane if the forces are gravity = 16.0 kN, downward; lift = 15.5 kN, upward; thrust = 1.2 kN, north; drag = 1.2 kN, south.

## Example 2.8

### Sliding a Chest

**Figure 2.20**
Sliding a chest across the floor.

To slide a chest that weighs 750 N across the floor at constant velocity, you must push it horizontally with a force of 450 N (Fig. 2.20). Find the contact force that the floor exerts on the chest.

**Strategy** The chest moves with constant velocity, so it is in equilibrium. The net force acting on it is zero. We will identify all the forces acting on the chest, draw an FBD, do a graphical addition of the forces, choose $x$- and $y$-axes, resolve the forces into their $x$- and $y$-components, and then set $\Sigma F_x = 0$ and $\Sigma F_y = 0$.

**Solution** Three forces are acting on the chest. The gravitational force $\vec{\mathbf{W}}$ has magnitude 750 N and is directed downward. Your push $\vec{\mathbf{F}}$ has magnitude 450 N and its direction is horizontal. The contact force due to the floor $\vec{\mathbf{C}}$ has unknown magnitude and direction. However, remembering that the chest is in equilibrium, upward and downward force components must balance, as must the horizontal force components. Therefore, $\vec{\mathbf{C}}$ must be roughly in the direction shown in the FBD (Fig. 2.21a), as is confirmed by adding the three forces graphically (Fig. 2.21b). The sum is zero because the tip of the last vector ends up at the tail of the first one.

Choosing the $x$-axis to the right and the $y$-axis up means that two of the three force vectors, $\vec{\mathbf{W}}$ and $\vec{\mathbf{F}}$, have one component that is zero:

$$W_x = 0 \quad \text{and} \quad W_y = -750\text{ N}$$

$$F_x = 450\text{ N} \quad \text{and} \quad F_y = 0$$

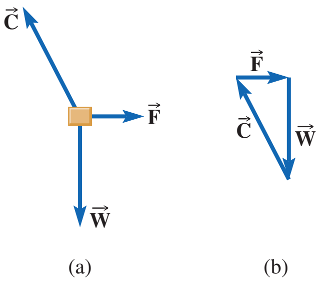



**Figure 2.21**
(a) A free-body diagram for the chest; (b) graphical addition of the three forces showing that the sum is zero.

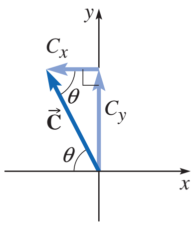



**Figure 2.22**
Finding the magnitude and direction of the contact force.

Now we set the $x$- and $y$-components of the net force each equal to zero because the chest is in equilibrium.

$$\sum F_x = W_x + F_x + C_x = 0 + 450\text{ N} + C_x = 0$$

$$\sum F_y = W_y + F_y + C_y = -750\text{ N} + 0 + C_y = 0$$

These equations tell us the components of $\vec{\mathbf{C}}$: $C_x = -450$ N and $C_y = +750$ N. Then the magnitude of the contact force is (Fig. 2.22)

$$C = \sqrt{C_x^2 + C_y^2} = \sqrt{(-450\text{ N})^2 + (750\text{ N})^2} = 870\text{ N}$$

$$\theta = \tan^{-1}\frac{\text{opposite}}{\text{adjacent}} = \tan^{-1}\frac{750\text{ N}}{450\text{ N}} = 59°$$

The contact force due to the floor is 870 N, directed 59° above the leftward horizontal ($-x$-axis).

**Discussion** The $x$- and $y$-components of the contact force and its magnitude and direction are all reasonable based on the graphical addition, so we can be confident that we did not make an error such as a sign error with one of the components.

Note that we didn't need to know any details about contact forces to solve this problem. We explore contact forces in more detail in Section 2.7.

**Practice Problem 2.8** The Chest at Rest

Suppose the same chest is at rest. You push it horizontally with a force of 110 N, but it does not budge. What is the contact force on the chest due to the floor during the time you are pushing?

## 2.5 INTERACTION PAIRS: NEWTON'S THIRD LAW OF MOTION

In Section 2.1, we learned that forces always exist in pairs. Every force is part of an interaction between two objects and each of those objects exerts a force on the other. We call the two forces an **interaction pair;** each force is the **interaction partner** of the other. When you push open a door, the door pushes you. When two cars collide, each exerts a force on the other. Note that interaction partners *always act on different objects*—the two objects that are interacting.

**Newton's third law of motion** says that interaction partners always have the *same magnitude* and are in *opposite directions.*

### Newton's Third Law of Motion

In an interaction between two objects, each object exerts a force on the other. These two forces are equal in magnitude and opposite in direction.

Equivalently, we can write

$$\vec{\mathbf{F}}\text{ (on } B \text{ by } A) = -\vec{\mathbf{F}}\text{ (on } A \text{ by } B) \quad (2\text{-}6)$$

Do not assume that Newton's third law is involved *every* time two forces *happen* to be equal and opposite—*it ain't necessarily so*! You will encounter many situations in which two equal and opposite forces act *on a single object.* These forces cannot be *interaction partners* because they act on the same object. Interaction partners act on *different objects,* one on each of the two objects that are interacting. Note also that interaction partners are always of the same type (both gravitational, or both magnetic, or both frictional, etc.).

We will use Newton's third law frequently when analyzing forces. For instance, in Conceptual Example 2.13, Newton's third law is used to analyze forces that act when a horse pulls a sleigh.

## Conceptual Example 2.9

### An Orbiting Satellite

Earth exerts a gravitational force on an orbiting communications satellite. What is the interaction partner of this force?

**Strategy** The question concerns a gravitational interaction between two objects: Earth and the satellite. In this interaction, each object exerts a gravitational force on the other.

**Solution** The interaction partner is the gravitational force exerted on the Earth by the satellite.

**Discussion** Does the satellite really exert a force on the Earth with the same magnitude as the force Earth exerts on the satellite? If so, why does the satellite orbit Earth rather than Earth orbiting the satellite? Newton's third law says that the interaction partners are equal in magnitude, but does not say that these two forces have equal *effects.* We will see in Chapter 3 that the effect of a net force on an object's motion depends on the object's mass. These two forces of equal magnitude have different effects due to the great discrepancy between the masses of the Earth and the satellite.

On the other hand, if a massive planet orbits a star in a relatively small orbit, the gravitational force that the planet exerts on the star can make the star wobble enough to be observed. The wobble enables astronomers to discover planets orbiting stars other than the Sun. The planets do not reflect enough light toward Earth to be seen, but their presence can be inferred from the effect they have on the star's motion.

**Practice Problem 2.9** Interaction Partner of a Surface Contact Force

In Example 2.8, the contact force exerted on the chest by the floor was 870 N, directed 59° above the leftward horizontal ($-x$-axis). Describe the interaction partner of this force—in other words, what object exerts it on what other object? What are the magnitude and direction of the interaction partner?

## CHECKPOINT 2.5

In the photo, two children are pulling on a toy. If they are exerting equal and opposite forces on the toy, are these two forces interaction partners? Why or why not?

**EVERYDAY PHYSICS DEMO**

The next time you go swimming, notice that you use Newton's third law to get the water to push you forward. When you push down and backward on the water with your arms and legs, the water pushes up and forward on you. The various swimming strokes are devised so that you exert as large a force as possible backward on the water during the power part of the stroke, and then as small a force as possible forward on the water during the return part of the stroke. Notice a similar effect when you are walking, skating, or skiing. To get the ground to push you forward, your feet push backward on the ground. Conceptual Example 2.13 explores these forces in more detail.

### Internal and External Forces

When we say that a soccer ball interacts with the Earth (gravity), with a player's foot, and with the air, we are treating the ball as a single entity. But the ball really consists of an enormous number of protons, neutrons, and electrons, all interacting with each other. The protons and neutrons interact with each other to form atomic nuclei; the nuclei interact with electrons to form atoms; interactions between atoms form molecules; and the molecules interact to form the structure of the thing we call a soccer ball. It would be difficult to have to deal with all of these interactions to predict the motion of a soccer ball.

**Defining a System** Let us call the set of particles that make up the soccer ball a **system.** Once we have defined a system, we can classify all the interactions that affect the system as either **internal** or **external** to the system. For an internal interaction, *both* interacting objects are part of the system. When we add up all the forces acting on the system to find the net force, every internal interaction contributes two forces—an interaction pair—that always add to zero. For an external interaction, *only one of the two interaction partners is exerted on the system.* The other partner is exerted on an object outside the system and does not contribute to the net force on the system. So to find the net force on the system, we can ignore all the internal forces and just add the external forces.

The insight that internal forces always add to zero is particularly powerful because the choice of what constitutes a system is completely arbitrary. We can choose *any* set of objects and define it to be a system. In one problem, it may be convenient to think of the soccer ball as a system; in another, we may choose a system consisting of both the soccer ball and the player's foot. The second choice might be useful if we do not have detailed information about the interaction between the foot and the ball.

## 2.6 GRAVITATIONAL FORCES

Now that we know how to add forces, we turn our attention to learning about a few forces in more detail, beginning with gravity. According to **Newton's law of universal gravitation,** any two objects exert gravitational forces on each other that are proportional to the masses ($m_1$ and $m_2$) of the two objects and inversely proportional to the square of the distance ($r$) between their centers. Strictly speaking, the law of gravitation as presented here only applies to point particles and symmetrical spheres. (The *point particle* is a common model in physics used when the size of an object is negligibly small and the internal structure is irrelevant.) Nevertheless, the law of gravitation is *approximately* true for any two objects if the distance between their centers is large relative to their sizes.

In mathematical language, the magnitude of the gravitational force is written:

$$F = \frac{Gm_1m_2}{r^2} \tag{2-7}$$

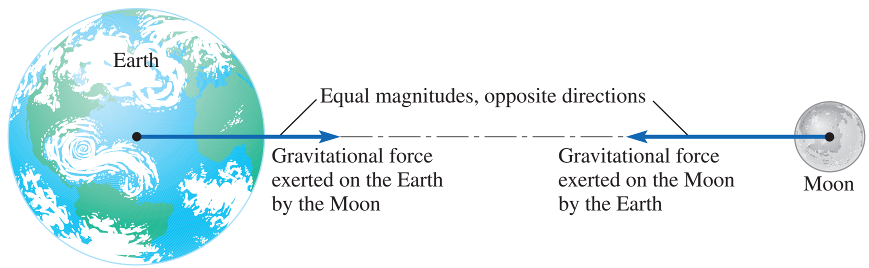



**Figure 2.23** Gravity is always an attractive force. The force that each body exerts on the other is equal in magnitude, even though the masses may be very different. The force exerted *on the Moon by the Earth* is of the same magnitude as the force exerted on the Earth by the Moon. The directions are opposite.

where the constant of proportionality ($G = 6.674 \times 10^{-11}$ N·m$^2$/kg$^2$) is called the **universal gravitational constant.** Equation (2-7) is only part of the law of universal gravitation because it gives only the magnitudes of the gravitational forces that each object exerts on the other. The directions are equally important: each object is pulled toward the other's center (Fig. 2.23). In other words, gravity is an attractive force. The forces on the two objects are equal in magnitude and the directions are opposite, as they must be since they form an interaction pair.

Gravitational forces exerted *by* ordinary objects on each other are so small as to be negligible in most cases (see Practice Problem 2.10). Gravitational forces exerted by Earth, on the other hand, are much larger due to Earth's large mass.

## Example 2.10

### Weight at High Altitude

When you are in a commercial airliner cruising at an altitude of 6.4 km (21 000 ft), by what percentage has your weight (as well as the weight of the airplane) changed compared with your weight on the ground?

**Strategy** Your weight is the magnitude of Earth's gravitational force exerted on you. Newton's law of universal gravitation gives the magnitude of the gravitational force at a distance $r$ from the center of the Earth. For your weight on the ground $W_1$, we can use the mean radius of the Earth $R_E$ as the distance between the Earth's center and you: $r_1 = R_E = 6.37 \times 10^6$ m (Fig. 2.24). At an altitude of $h = 6.4 \times 10^3$ m above the surface, your weight is $W_2$ and your distance from Earth's center is $r_2 = R_E + h$. Your mass $m$, the mass of the Earth $M_E$ ($= 5.97 \times 10^{24}$ kg), and $G$ are the same in the two cases, so it is efficient to write a ratio of the weights and let those factors cancel out.

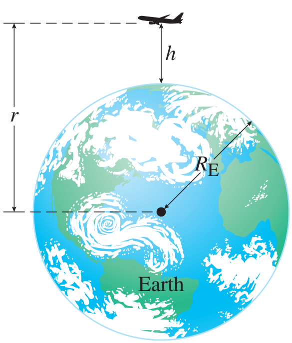



**Figure 2.24**
The gravitational force depends on the distance $r$ to the *center* of the Earth. At an altitude $h$, $r = R_E + h$.

**Solution** The ratio of your weight in the airplane to your weight on the ground is

$$\frac{W_2}{W_1} = \frac{\dfrac{\cancel{GM_E m}}{r_2^2}}{\dfrac{\cancel{GM_E m}}{r_1^2}} = \frac{r_1^2}{r_2^2} = \frac{R_E{}^2}{(R_E + h)^2}$$

$$= \left(\frac{6.37 \times 10^6 \text{ m}}{6.37 \times 10^6 \text{ m} + 6.4 \times 10^3 \text{ m}}\right)^2 = 0.998$$

Since 0.998 = 1 − 0.002 and 0.002 = 0.2/100, your weight decreases by 0.2%.

**Discussion** Although 6400 m may seem like a significant altitude to us, it's a small fraction of the Earth's radius (0.10%), so the weight change is a small percentage. When judging whether a quantity is small or large, always ask: "Small (or large) compared with what?"

### Practice Problem 2.10 A Creative Defense

After an automobile collision, one driver claims that the gravitational force between the two cars caused the collision. Estimate the magnitude of the gravitational force exerted by one car on another when they are driving side-by-side in parallel lanes and comment on the driver's claim.

## Gravitational Field Strength

For an object near Earth's surface, the distance between the object and the Earth's center is very nearly equal to the Earth's mean radius, $R_E = 6.37 \times 10^6$ m. The mass of the Earth is $M_E = 5.97 \times 10^{24}$ kg, so the weight of an object of mass $m$ near Earth's surface is

$$W = \frac{GM_E m}{R_E^2} = m\left(\frac{GM_E}{R_E^2}\right) \quad \textbf{(2-8)}$$

**CONNECTION:**

Chapter 3 shows that 1 N/kg = 1 m/s$^2$. For now, we write the units of $g$ as N/kg to emphasize that $g$ relates weight (in newtons) to mass (in kilograms).

Notice that for objects near Earth's surface, the constants in the parentheses are always the same and the weight of the object is proportional to its mass. Rather than recalculate that combination of constants over and over, we call the combination the **gravitational field strength** $g$ near Earth's surface:

$$g = \frac{GM_E}{R_E^2} = \frac{6.674 \times 10^{-11}\ \text{N}\cdot\text{m}^2\cdot\text{kg}^{-2} \times (5.97 \times 10^{24}\ \text{kg})}{(6.37 \times 10^6\ \text{m})^2} \approx 9.8\ \text{N/kg} \quad \textbf{(2-9)}$$

The units *newtons per kilogram* reinforce the conclusion that weight is proportional to mass: $g$ tells us how many newtons of gravitational force are exerted on an object for every kilogram of the object's mass. The weight of a 1.0-kg object near Earth's surface is 9.8 N (2.2 lb). Using $g$, the weight of an object of mass $m$ near Earth's surface is usually written as follows:

**Relationship between mass and weight:**

$$W = mg \quad \textbf{(2-10a)}$$

We can rewrite Eq. (2-10a) in vector form:

$$\vec{\mathbf{W}} = m\vec{\mathbf{g}} \quad \textbf{(2-10b)}$$

Here $\vec{\mathbf{W}}$ stands for the gravitational force and $\vec{\mathbf{g}}$ is called the gravitational field; the direction of both is downward. The italic (scalar) symbol $g$ is the *magnitude* of a vector, so its value is *never negative.*

**Variations in Earth's Gravitational Field** The Earth is not a perfect sphere; it is slightly flattened at the poles. Since the distance from the surface to the center of the Earth is smaller there, the field strength at sea level is greatest at the poles (9.832 N/kg) and smallest at the equator (9.814 N/kg). Altitude also matters; as you climb above sea level, your distance from Earth's center increases and the field strength decreases. Tiny local variations in the field strength are also caused by geologic formations. On top of dense bedrock, $g$ is a little greater than above less dense rock. Geologists and geophysicists measure these variations to study Earth's structure and also to locate deposits of various minerals, water, and oil. The device they use, a *gravimeter,* is essentially a mass hanging on a spring. As the gravimeter is carried from place to place, the extension of the spring increases where $g$ is larger and decreases where $g$ is smaller. The mass hanging from the spring does not change, but its weight does ($W = mg$).

Furthermore, due to Earth's rotation, the *effective* value of $g$ that we measure in a coordinate system attached to Earth's surface is slightly less than the true value of the field strength. This effect is greatest at the equator, where the effective value of $g$ is 9.784 N/kg, about 0.3% smaller than the true value of $g$. The effect gradually decreases with latitude to zero at the poles. We learn more about this effect in Chapter 5.

The most important thing to remember from this is that, unlike $G$, $g$ is *not* a universal constant. The value of $g$ is a function of position. Near Earth's surface, the variations are small, so we can adopt an average value as a default:

**Average value of $g$ near Earth's surface:**

$$g = 9.80\ \text{N/kg}$$

Please use this value for $g$ near Earth's surface unless the statement of a problem gives a different value.

## Example 2.11

### "Weighing" Figs in Kilograms

In most countries other than the United States, produce is sold in mass units (grams or kilograms) rather than in force units (pounds or newtons). The scale still measures a force, but the scale is calibrated to show the mass of the produce instead of its weight. What is the weight of 350 g of fresh figs, in newtons and in pounds?

**Strategy** Weight is mass times the gravitational field strength. We will assume $g = 9.80$ N/kg. The weight in newtons can be converted to pounds using the conversion factor 1 N = 0.2248 lb.

**Solution** The weight of the figs in newtons is

$$W = mg = 0.35 \text{ kg} \times 9.80 \text{ N/kg} = 3.43 \text{ N}$$

Converting to pounds,

$$W = 3.43 \text{ N} \times 0.2248 \text{ lb/N} = 0.771 \text{ lb}$$

The figs weigh 3.4 N, or 0.77 lb.

**Discussion** This is the weight of the figs at a location where $g$ has its average value of 9.80 N/kg. The figs would weigh a little more in the northern city of St. Petersburg, Russia, where $g$ is larger, and a little less in Quito, Ecuador, where $g$ is smaller.

**Practice Problem 2.11** Figs on the Moon

What would those figs weigh on the surface of the Moon, where $g = 1.62$ N/kg?

Equation (2-10a) can be used to find the weight of an object at or above the surface of *any* planet or moon, but the value of $g$ will be different due to the different mass $M$ of the planet or moon and the different distance $r$ from the planet's center:

$$g = \frac{GM}{r^2} \qquad (2\text{-}11)$$

For instance, by substituting the mass and radius of Mars into Eq. (2-11), we find that $g = 3.7$ N/kg on the surface of Mars.

### CHECKPOINT 2.6

If you climb Mt. McKinley, what happens to the weight of your gear? What happens to its mass?

## 2.7 CONTACT FORCES

We have already done some problems involving forces exerted between two solid objects in contact. Now we look at those forces in more detail. In Example 2.8, we resolved the contact force on a sliding chest into components perpendicular to and parallel to the contact surface. It is often convenient to think of these components as two separate but related contact forces: the *normal force* and the *frictional force.*

**CONNECTION:**

*Normal force* and *frictional force* are just names given to two perpendicular components of a surface contact force.

### Normal Force

A contact force perpendicular to the contact surface that prevents two solid objects from passing through one another is called the **normal force.** (In geometry, the word *normal* means *perpendicular.*) Consider a book resting on a horizontal table surface. The

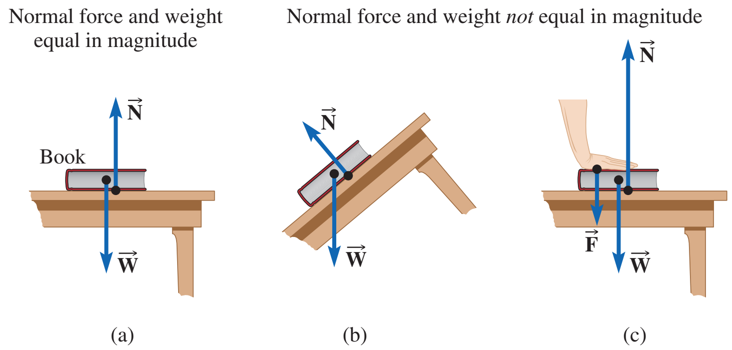



**Figure 2.25** (a) The normal force is equal in magnitude to the weight of the book; the two forces sum to zero. (b) On an incline, the normal force is smaller than the weight of the book and is *not vertical.* (c) If you push down on the book ($\vec{\mathbf{F}}$), the normal force on the book due to the table is larger than the book's weight.

normal force due to the table must have just the right magnitude to keep the book from falling through the table. If no other vertical forces act, the normal force on the book is equal in magnitude to the book's weight because the book is in equilibrium (Fig. 2.25a).

According to Newton's third law, two objects in contact exert equal and opposite normal forces on one another; each pushes the other away. In our example, a downward normal force is exerted on the table by the book. In *everyday* language, we might say that the table "feels the book's weight." That is not an accurate statement in the language of physics. The table cannot "feel" the gravitational force on the book; the table can only feel forces exerted *on the table.* What the table does "feel" is the normal force—a *contact* force—exerted on the table by the book.

If the table's surface is horizontal, the normal force on the book will be vertical and equal in magnitude to the book's weight. If the surface of the table is *not* horizontal, the normal force is not vertical and is not equal in magnitude to the weight of the book. Remember that the normal force is *perpendicular to the contact surface* (Fig. 2.25b). Even on a horizontal surface, if there are other vertical forces acting on the book, then the normal force is *not* equal in magnitude to the book's weight (Fig. 2.25c). Never *assume* anything about the magnitude of the normal force. In general, we can figure out what the magnitude of the normal force must be in various situations if we have enough information about other forces.

**Figure 2.26** The book compresses the "atomic springs" in the table until they push up on the book to hold it up. The slight decrease in the distance between atoms is greatly exaggerated here.

**Origin of the Normal Force** How does the table "know" how hard to push on the book? First imagine putting the book on a bathroom scale instead of the table. A spring inside the scale provides the upward force. The spring "knows" how hard to push because, as it is compressed, the force it exerts increases. When the book reaches equilibrium, the spring is exerting just the right amount of force, so there is no tendency to compress it further. The spring is compressed until it pushes up with a force equal to the book's weight. If the spring were stiffer, it would exert the same upward force but with less compression.

The forces that bind atoms together in a rigid solid, like the table, act like extremely stiff springs that can provide large forces with little compression—so little that it's usually not noticed. The book makes a tiny indentation in the surface of the table (Fig. 2.26); a heavier book would make a slightly larger indentation. If the book were to be placed on a soft foam surface, the indentation would be much more noticeable.

## CHECKPOINT 2.7

Your laptop is resting on the surface of your desk, which stands on four legs on the floor. Identify the normal forces acting on the desk and give their directions.

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## Friction

A contact force *parallel* to the contact surface is called **friction.** We distinguish two types: **static friction** and **kinetic** (or **sliding) friction.** When the two objects are slipping or sliding across one another, as when a loose shingle slides down a roof, the friction is kinetic. When no slipping or sliding occurs, such as between the tires of a car parked on a hill and the road surface, the friction is called static. Static friction acts to prevent objects from *starting* to slide; kinetic friction acts to try to make sliding objects stop sliding. Note that two objects in contact with one another that move with the same velocity exert *static* frictional forces on one another, because there is no *relative* motion between the two. For example, if a conveyor belt carries an air freight package up an incline and the package is not sliding, the two move with the same velocity and the friction is *static*.

**Static Friction** Frictional forces are complicated on the microscopic level and are an active field of current research. Despite the complexities, we can make some approximate statements about the frictional forces between dry, solid surfaces. In a simplified model, the maximum magnitude of the force of static friction $f_{s,\,max}$ that can occur in a particular situation is proportional to the magnitude of the normal force $N$ acting between the two surfaces.

$$f_{s,\,max} \propto N$$

If you want better traction between the tires of a rear-wheel-drive car and the road, it helps to put something heavy in the trunk to increase the normal force between the tires and the road.

The constant of proportionality is called the **coefficient of static friction** (symbol $\mu_s$):

**Maximum force of static friction:**

$$f_{s,\,max} = \mu_s N \quad \text{(2-12)}$$

Since $f_{s,max}$ and $N$ are both magnitudes of forces, $\mu_s$ is a dimensionless number. Its value depends on the condition and nature of the surfaces. Equation (2-12) provides only an *upper limit* on the force of static friction in a particular situation. The actual force of friction in a given situation is not necessarily the maximum possible. It tells us only that, if sliding does not occur, the magnitude of the static frictional force is less than or equal to this upper limit:

$$f_s \le \mu_s N \quad \text{(2-13)}$$

**Kinetic (Sliding) Friction** For sliding or kinetic friction, the force of friction is only weakly dependent on the speed and is roughly proportional to the normal force. In the simplified model we will use, the force of kinetic friction is assumed to be proportional to the normal force and independent of speed:

**Force of kinetic (sliding) friction:**

$$f_k = \mu_k N \quad \text{(2-14)}$$

where $f_k$ is the magnitude of the force of kinetic friction and $\mu_k$ is called the **coefficient of kinetic friction.** The coefficient of static friction is always larger than the coefficient of kinetic friction for an object on a given surface. On a horizontal surface, a larger force is required to start the object moving than is required to keep it moving at a constant velocity.

**Direction of Frictional Forces** Equations (2-12) through (2-14) relate only the *magnitudes* of the frictional and normal forces on an object. Remember that the frictional force is perpendicular to the normal force between the same two surfaces. Friction is always parallel to the contact surface, but there are many directions parallel to a given contact surface. Here are some rules of thumb for determining the direction of a frictional force.

- The static frictional force acts in whatever direction necessary to prevent the objects from beginning to slide or slip.
- Kinetic friction acts in a direction that tends to make the sliding or slipping stop. If a book slides to the left along a table, the table exerts a kinetic frictional force on the book to the right, in the direction opposite to the motion of the book.
- From Newton's third law, frictional forces come in interaction pairs. If the table exerts a frictional force on the sliding book to the right, the book exerts a frictional force on the table to the *left* with the same magnitude.

## Example 2.12

### Coefficient of Kinetic Friction for the Sliding Chest

Example 2.8 involved sliding a 750-N chest to the right at constant velocity by pushing it with a horizontal force of 450 N. We found that the contact force on the chest due to the floor had components $C_x = -450$ N and $C_y = +750$ N, where the $x$-axis points to the right and the $y$-axis points up (see Fig. 2.22). What is the coefficient of kinetic friction for the chest-floor surface?

**Strategy** To find the coefficient of friction, we need to know what the normal and frictional forces are. They are the components of the contact force that are perpendicular and parallel to the contact surface. Since the surface is horizontal (in the $x$-direction), the $x$-component of the contact force is friction and the $y$-component is the normal force.

**Solution** The magnitude of the force due to sliding friction is $f_k = |C_x| = 450$ N. The magnitude of the normal force is $N = |C_y| = 750$ N. Now we can calculate the coefficient of kinetic friction from $f_k = \mu_k N$:

$$\mu_k = \frac{f_k}{N} = \frac{450\ \text{N}}{750\ \text{N}} = 0.60$$

**Discussion** If we had written $f_k = C_x = -450$ N, we would have ended up with a negative coefficient of friction. The coefficient of friction is a relationship between the *magnitudes* of two forces, so it cannot be negative.

**Practice Problem 2.12** Chest at Rest

Suppose the same chest is at rest. You push to the right with a force of 110 N, but the chest does not budge. What are the normal and frictional forces on the chest due to the floor while you are pushing? Explain why you do not need to know the coefficient of static friction to answer this question.

## Conceptual Example 2.13

### Horse, Sleigh, and Newton's Third Law

A horse pulls a sleigh to the right at constant velocity on level ground (Fig. 2.27). The horse exerts a horizontal force $\vec{\mathbf{F}}_{sh}$ on the sleigh. (The subscripts indicate the force on the sleigh due to the horse.) (a) Draw three FBDs, one for the horse, one for the sleigh, and one for the system horse + sleigh. (b) To make the sleigh increase its velocity, there must be a nonzero net force to the right acting on the sleigh. Suppose the horse pulls harder ($F_{sh}$ increases in magnitude). According to Newton's third law, the sleigh always pulls back on the horse with a force of *the same* magnitude as the force with which the horse pulls the sleigh. Does this mean that no matter how hard it pulls, the horse can never make the net force on the sleigh nonzero? Explain. (c) Identify the interaction partner of each force acting on the sleigh.


**Figure 2.27**
Horse pulling sleigh.

*continued on next page*

## Conceptual Example 2.13 continued

**Strategy** (a) In each FBD, we include only the *external* forces acting on that system. All three systems move with constant velocity, so the net force on each is zero. (b) Looking at the FBD for the sleigh, we can determine the conditions under which the net force on the sleigh can be nonzero. (c) For a force exerted on the sleigh by *X,* its interaction partner must be the force exerted on *X* by the sleigh.

**Solution and Discussion** (a) If we think of the normal and frictional forces as separate forces, then there are four forces acting on the sleigh: the force exerted by the horse $\vec{\mathbf{F}}_{sh}$, the gravitational force due to Earth $\vec{\mathbf{F}}_{sE}$, the normal force on the sleigh due to the ground $\vec{\mathbf{N}}_{sg}$, and kinetic (sliding) friction due to the ground $\vec{\mathbf{f}}_{sg}$. Figure 2.28 shows the FBD for the sleigh. The net force is zero, so its horizontal and vertical components must each be zero: $\vec{\mathbf{F}}_{sh} + \vec{\mathbf{f}}_{sg} = 0$ and $\vec{\mathbf{N}}_{sg} + \vec{\mathbf{F}}_{sE} = 0$.

Similarly, four forces are acting on the horse: the force exerted by the sleigh $\vec{\mathbf{F}}_{hs}$, the gravitational force $\vec{\mathbf{F}}_{hE}$, the normal force due to the ground $\vec{\mathbf{N}}_{hg}$, and friction due to the ground $\vec{\mathbf{f}}_{hg}$. Newton's third law says that $\vec{\mathbf{F}}_{hs} = -\vec{\mathbf{F}}_{sh}$; the sleigh pulls back on the horse with a force equal in magnitude to the forward pull of the horse on the sleigh. Therefore, $\vec{\mathbf{F}}_{hs}$ is to the left and has the same magnitude as $\vec{\mathbf{F}}_{sh}$. The horse is in equilibrium, so $\vec{\mathbf{F}}_{hs} + \vec{\mathbf{f}}_{hg} = 0$ and $\vec{\mathbf{N}}_{hg} + \vec{\mathbf{F}}_{hE} = 0$. The first of these equations means that the frictional force has to be to the *right.* How does the horse get friction to push it *forward?* By pushing *backward* on the ground with its feet. We all do the same thing when taking a step; by pushing backward on the ground, we get the ground to push forward on us. This is *static* friction because the horse's hoof is not sliding along the ground. If there were no friction (imagine the ground to be icy), the hoof might slide backward. Static friction acts to prevent sliding, so the frictional force on the hoof is forward. Figure 2.29 shows the FBD for the horse.

Of the eight forces acting either on the horse or on the sleigh, two are internal forces for the horse + sleigh system: $\vec{\mathbf{F}}_{sh}$ and $\vec{\mathbf{F}}_{hs}$. They add to zero since they are interaction partners, so we can omit them from the FBD for the system (Fig. 2.30). The two frictional forces on the system horse + sleigh are *not* interaction partners, but they are equal in magnitude and opposite in direction. From the FBDs, $\vec{\mathbf{f}}_{hg} = -\vec{\mathbf{F}}_{hs}$ and $\vec{\mathbf{f}}_{sg} = -\vec{\mathbf{F}}_{sh}$. Because $\vec{\mathbf{F}}_{hs}$ and $\vec{\mathbf{F}}_{sh}$ are interaction partners, they are equal and opposite. Therefore, $\vec{\mathbf{f}}_{hg}$ and $\vec{\mathbf{f}}_{sg}$ are equal and opposite. The system is in equilibrium.

(b) The FBD for the sleigh (see Fig. 2.28) shows that if the horse pulls the sleigh with a force greater in magnitude than the force of friction on the sleigh ($F_{sh} > f_{sg}$), then the net force on the sleigh is nonzero and to the right. From Fig. 2.29, we need $f_{hg} > F_{hs}$ to have a nonzero net force to the right on the horse. So the frictional force on the horse would have to increase to enable it to pull the sleigh with a greater force. Then in Fig. 2.30, the two frictional forces are no longer equal in magnitude. The forward frictional force on the horse is greater than the backward frictional force on the sleigh, so the net force on the system horse + sleigh is to the right.

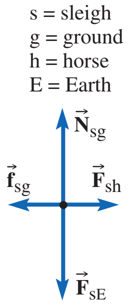


**Figure 2.28**

Free-body diagram for the sleigh. The subscripts identify the objects involved in the interaction. For example, $\vec{\mathbf{F}}_{sh}$ stands for the force on the sleigh due to the horse. Since the FBD is for the sleigh, we include only forces exerted *on* the sleigh, so the first subscript is always "s."

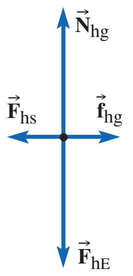


**Figure 2.29**

Free-body diagram for the horse. $\vec{\mathbf{F}}_{hs}$, the force exerted on the horse by the sleigh, is the interaction partner of $\vec{\mathbf{F}}_{sh}$ in Fig. 2.28, the force exerted on the sleigh by the horse. Therefore, $\vec{\mathbf{F}}_{hs} = -\vec{\mathbf{F}}_{sh}$.

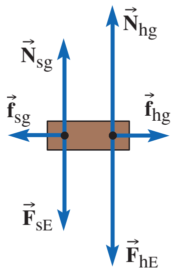


**Figure 2.30**

Free-body diagram for the system, horse, and sleigh. The internal forces $\vec{\mathbf{F}}_{sh}$ and $\vec{\mathbf{F}}_{hs}$ are omitted—they form an interaction pair, so they add to zero.

(c)

| Force Exerted on Sleigh | Interaction Partner |
|---|---|
| Force on the sleigh due to the horse $\vec{\mathbf{F}}_{sh}$ | Force on the horse due to the sleigh $\vec{\mathbf{F}}_{hs}$ |
| Gravitational force on the sleigh due to Earth $\vec{\mathbf{F}}_{sE}$ | Gravitational force on Earth due to the sleigh $\vec{\mathbf{F}}_{Es}$ |
| Normal force on the sleigh due to the ground $\vec{\mathbf{N}}_{sg}$ | Normal force on the ground due to the sleigh $\vec{\mathbf{N}}_{gs}$ |
| Friction on the sleigh due to the ground $\vec{\mathbf{f}}_{sg}$ | Friction on the ground due to the sleigh $\vec{\mathbf{f}}_{gs}$ |

### Practice Problem 2.13 Passing a Truck

A car is moving north and speeding up to pass a truck on a level road. The combined contact force exerted *on the road by all four tires* has vertical component 11.0 kN downward and horizontal component 3.3 kN southward. The drag force exerted on the car by the air is 1.2 kN southward. (a) Draw the FBD for the car. (b) What is the weight of the car? (c) What is the net force acting on the car?

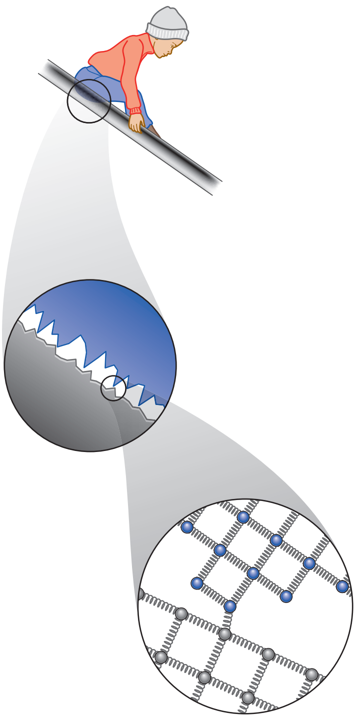

**Figure 2.31** Friction is caused by bonds between atoms that form between the "high points" of the two surfaces that come into contact.

**Microscopic Origin of Friction** What looks like the smooth surface of a solid to the unaided eye is generally quite rough on a microscopic scale (Fig. 2.31). Friction is caused by atomic or molecular bonds between the "high points" on the surfaces of the two objects. These bonds are formed by microscopic electromagnetic forces that hold the atoms or molecules together. If the two objects are pushed together harder, the surfaces deform a little more, enabling more "high points" to bond. That is why the force of kinetic friction and the maximum force of static friction are proportional to the normal force. A bit of lubricant drastically decreases the frictional forces, because the two surfaces can float past each other without many of the "high points" coming into contact.

In static friction, when these molecular bonds are stretched, they pull back harder. The bonds have to be broken before sliding can begin. Once sliding begins, molecular bonds are continually made and broken as "high points" come together in a hit-or-miss fashion. These bonds are generally not as strong as those formed in the absence of sliding, which is why $\mu_s > \mu_k$.

For dry, solid surfaces, the amount of friction depends on how smooth the surfaces are and how many contaminants are present on the surface. Does polishing two steel surfaces decrease the frictional forces when they slide across each other? Not necessarily. In an extreme case, if the surfaces are extremely smooth and all surface contaminants are removed, the steel surfaces form a "cold weld"—essentially, they become one piece of steel. The atoms bond as strongly with their new neighbors as they do with the old.

**Application: Equilibrium on an Inclined Plane** Suppose we wish to pull a large box up a *frictionless* incline to a loading dock platform. Figure 2.32 shows the three forces acting on the box. $\vec{\mathbf{F}}_a$ represents the applied force with which we pull. The force is parallel to the incline. If we choose the *x*- and *y*-axes to be horizontal and vertical, respectively, then two of the three forces have both *x*- and *y*-components. On the other hand, if we choose the *x*-axis parallel to the incline and the *y*-axis perpendicular to it, then only one of the three forces has both *x*- and *y*-components (the gravitational force).

With axes chosen, the weight of the box is then resolved into two perpendicular components (Fig. 2.33a). To find the *x*- and *y*-components of the gravitational force $\vec{\mathbf{W}}$, we must determine the angle that $\vec{\mathbf{W}}$ makes with one of the axes. The right triangle of

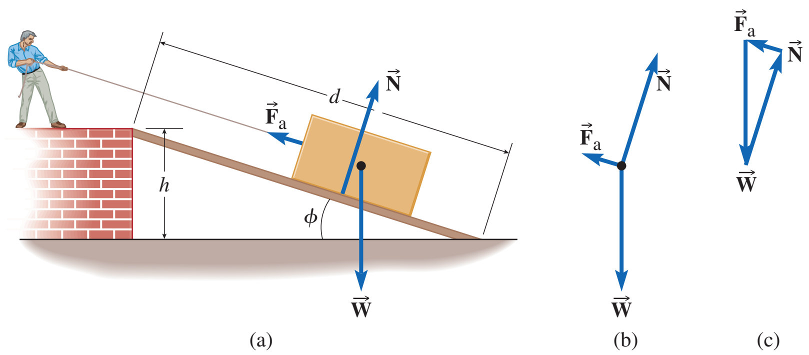


**Figure 2.32** (a) Forces acting on a box of mass *m* as it is pulled up an incline. (b) Free-body diagram for the box. (c) Graphical addition showing that, *if the box moves with constant velocity,* the net force is zero.

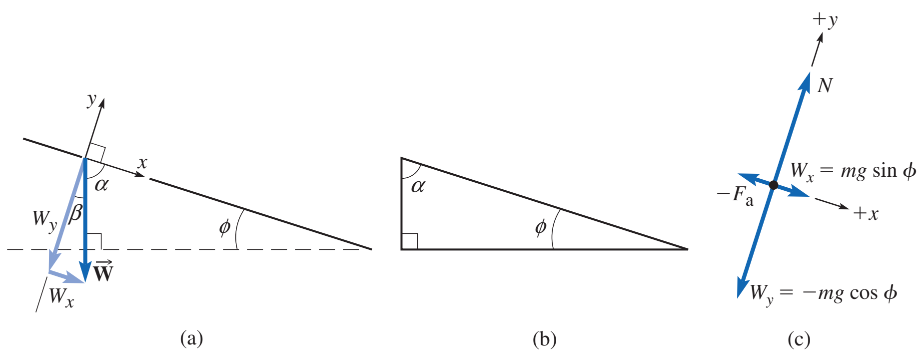


**Figure 2.33** (a) Resolving the weight into components parallel to and perpendicular to the incline. (b) A right triangle shows that $\alpha + \phi = 90°$ . (c) Free-body diagram for the box on the incline with the gravitational force separated into *x*- and *y*-components

Fig. 2.33b shows that $\alpha + \phi = 90°$ , since the interior angles of a triangle add up to 180°. The $x$- and $y$-axes are perpendicular, so $\alpha + \beta = 90°$ . Therefore, $\beta = \phi$.

The $y$-component of $\vec{\mathbf{W}}$ is perpendicular to the surface of the incline. From Fig. 2.33a, the side parallel to the $y$-axis is adjacent to angle $\beta$, so

$$\cos \beta = \frac{\text{adjacent}}{\text{hypotenuse}} = \frac{|W_y|}{|W|}$$

Since $W_y$ is negative and $W = mg$,

$$W_y = -mg \cos \beta = -mg \cos \phi$$

The $x$-component of the weight tends to make the box slide down the incline (in the $+x$-direction). Using the same triangle,

$$W_x = +mg \sin \phi$$

When the box is pulled with a force equal in magnitude to $W_x$ up the incline (in the negative $x$-direction), it will slide up with constant velocity. The component of the box's weight perpendicular to the incline is supported by the normal force $\vec{\mathbf{N}}$ that pushes the box away from the incline. Figure 2.33c is an FBD in which the gravitational force is separated into its $x$- and $y$-components.

If the box is in equilibrium, whether at rest or moving along the incline at constant velocity, the force components along each axis sum to zero:

$$\sum F_x = (-F_a) + mg \sin \phi = 0$$

and

$$\sum F_y = N + (-mg \cos \phi) = 0$$

The normal force is *not* equal in magnitude to the weight and it does not point straight up. If the applied force has magnitude $mg \sin \phi$, we can pull the box up the incline at constant velocity. If friction acts on the box, we must pull with a force greater than $mg \sin \phi$ to slide the box up the incline at constant velocity.

## Example 2.14

### Pushing a Safe up an Incline

A new safe is being delivered to the Corner Book Store. It is to be placed in the wall at a height of 1.5 m above the floor. The delivery people have a portable ramp, which they plan to use to help them push the safe up and into position. The mass of the safe is 510 kg, the coefficient of static friction along the incline is $\mu_s = 0.42$, and the coefficient of kinetic friction along the incline is $\mu_k = 0.33$. The ramp forms an angle $\theta = 15°$ above the horizontal. (a) How hard do the movers have to push to start the safe moving up the incline? Assume that they push in a direction parallel to the incline. (b) To slide the safe up at a constant speed, with what magnitude force must the movers push?

**Strategy** (a) When the safe *starts* to move, its velocity is changing, so the safe is *not* in equilibrium. Nevertheless, to find the minimum applied force to start the safe moving, we can find the *maximum* applied force for which the safe *remains at rest*—an equilibrium situation. (b) The safe is in equilibrium as it slides with a constant velocity. Both parts of the problem can be solved by drawing the FBD, choosing axes, and setting the $x$- and $y$-components of the net force equal to zero.

**Solution** First we draw a diagram to show the forces acting (Fig. 2.34). When the crate is in equilibrium, these forces must add to zero. Figure 2.35a is a free-body diagram for the crate. Figure 2.35b shows the graphical addition of the four forces giving a net force of zero.

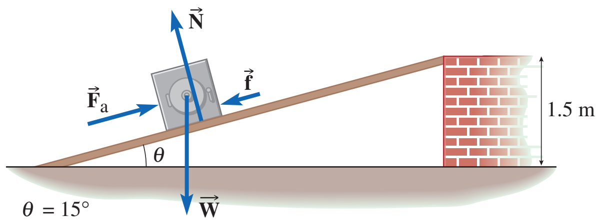


**Figure 2.34**
Forces acting on the safe as it is moved up the incline.

*continued on next page*

## Example 2.14 continued

Before resolving the forces into components, we must choose $x$- and $y$-axes. To use the coefficient of friction, we have to resolve the contact force on the safe due to the incline into components *parallel and perpendicular to the incline*—friction and the normal force, respectively—rather than into horizontal and vertical components. Therefore, we choose $x$- and $y$-axes parallel and perpendicular to the incline so friction is along the $x$-axis and the normal force is along the $y$-axis.

The gravitational force $\vec{\mathbf{W}}$ can be resolved into its components: $W_x = -mg \sin\theta$ and $W_y = -mg\cos\theta$ (Fig. 2.35c). Now we draw the FBD with $\vec{\mathbf{W}}$ replaced by its components (Fig. 2.35d).

(a) Suppose that the safe is initially at rest. As the movers start to push, $F_a$ gets larger and the force of static friction gets larger to "try" to keep the safe from sliding. Eventually, at some value of $F_a$, static friction reaches its maximum possible value $\mu_s N$. If the movers continue to push harder, increasing $F_a$ further, the force of static friction cannot increase past its maximum value $\mu_s N$, so the safe starts to slide. The direction of the frictional force is along the incline and downward since friction is "trying" to keep the safe from sliding *up* the incline.

The normal force is *not* equal in magnitude to the weight of the safe. To find the normal force, sum the $y$-components of the forces:

$$\sum F_y = N + (-mg\cos\theta) = 0$$

Then $N = mg\cos\theta$. The normal force is *less than the weight* since $\cos\theta < 1$.

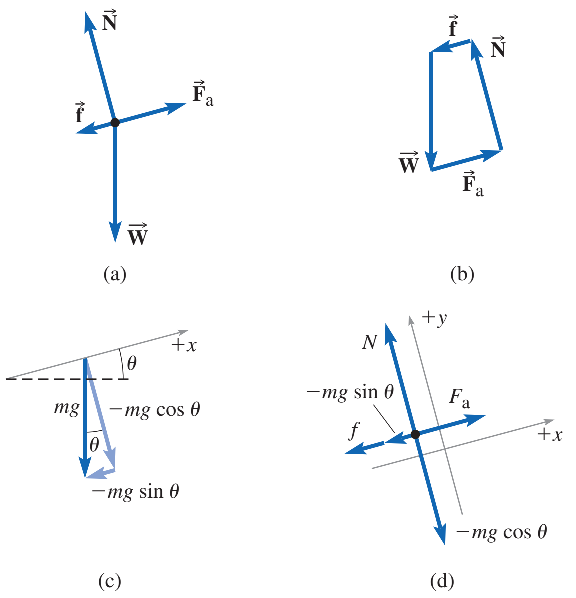


**Figure 2.35**

(a) Free-body diagram for the safe. (b) If the safe is in equilibrium, the forces must add to give a zero net force. (c) Resolving the weight into $x$- and $y$-components. (d) An FBD in which the weight is replaced with its $x$- and $y$-components.

When the movers push with the largest force for which the safe does *not* slide,

$$\sum F_x = F_{ax} + f_x + W_x + N_x = 0$$

The applied force is in the $+x$-direction, so $F_{ax} = +F_a$. The frictional force has its maximum magnitude and is in the $-x$-direction, so $f_x = -f_{s,max} = -\mu_s N = -\mu_s mg\cos\theta$. From the FBD, $W_x = -mg\sin\theta$ and $N_x = 0$. Then,

$$\sum F_x = F_a - \mu_s mg\cos\theta - mg\sin\theta + 0 = 0$$

Solving for $F_a$,

$$F_a = mg(\mu_s\cos\theta + \sin\theta)$$
$$= 510\text{ kg} \times 9.80\text{ m/s}^2 \times (0.42 \times \cos 15° + \sin 15°)$$
$$= 3300\text{ N}$$

An applied force that *exceeds* 3300 N starts the box moving up the incline.

(b) Once the safe is sliding, the movers need only push hard enough to make the net force on the safe equal to zero if they want the safe to slide at constant velocity. We are now dealing with sliding friction, so the frictional force is now $f_x = -\mu_k N = -\mu_k mg\cos\theta$.

$$\sum F_x = F_{ax} + f_x + W_x + N_x$$
$$= F_a - \mu_k mg\cos\theta - mg\sin\theta + 0$$
$$= 0$$
$$F_a = mg(\mu_k\cos\theta + \sin\theta)$$
$$= 510\text{ kg} \times 9.80\text{ m/s}^2 \times (0.33 \times \cos 15° + \sin 15°)$$
$$= 2900\text{ N}$$

The movers push with a force $\vec{\mathbf{F}}_a$ of magnitude 2900 N directed up the incline. Despite the friction that opposes the safe's motion, the force exerted by the movers is still less than what they would need to exert to lift the safe straight up (5000 N).

**Discussion** In (b), the expression $F_a = mg(\mu_k\cos\theta + \sin\theta)$ shows that the applied force up the incline has to balance the sum of two forces down the incline: the frictional force ($\mu_k mg\cos\theta$) and the component of the gravitational force down the incline ($mg\sin\theta$). This balance of forces is shown graphically in the FBD (Fig. 2.35d).

## Practice Problem 2.14 Smoothing the Infield Dirt

During the seventh-inning stretch of a baseball game, groundskeepers drag mats across the infield dirt to smooth it. A groundskeeper is pulling a mat at a constant velocity by applying a force of 120 N at an angle of 22° above the horizontal. The coefficient of kinetic friction between the mat and the ground is 0.60. Find (a) the magnitude of the frictional force between the dirt and the mat and (b) the weight of the mat.

**EVERYDAY PHYSICS DEMO**

To estimate the coefficient of static friction between a coin and the cover of your physics book, place the coin on the book and slowly lift the cover. Note the angle of the cover when the coin starts to slide. Explain how you can use this angle to find the coefficient of static friction. Can you devise an experiment to find the coefficient of kinetic friction?

Now try two different coins with different masses. Do they start to slide at about the same angle? If not, which one starts to slide first—the more massive coin or the less massive one?

## 2.8 TENSION

Consider a heavy chandelier hanging by a chain from the ceiling (Fig. 2.36a). The chandelier is in equilibrium, so the upward force on it due to the chain is equal in magnitude to the chandelier's weight. With what force does the chain pull downward on the ceiling? The ceiling has to pull up with a force equal to the total weight of the chain and the chandelier. The interaction partner of this force—the force the chain exerts on the ceiling—is equal in magnitude and opposite in direction. Therefore, if the weight of the chain is negligibly small compared with the weight of the chandelier, then the chain exerts forces of equal magnitude at its two ends. The forces at the ends would *not* be equal, however, if you grabbed the chain in the middle and pulled it up or down or if we could not ignore the weight of the chain. We can generalize this observation:

An *ideal* cord (or rope, string, tendon, cable, or chain) pulls in the direction of the cord with forces of equal magnitude on the objects attached to its ends as long as no external force is exerted on it anywhere between the ends. An ideal cord has zero mass and zero weight.

A single link of the chain (Fig. 2.36b) is pulled at both ends by the neighboring links. The magnitude of these forces is called the **tension** in the chain. Similarly, a little segment of a cord is pulled at both its ends by the tension in the neighboring pieces of the cord. If the segment is in equilibrium, then the net force acting on it is zero. As long as there are no other forces exerted on the segment, the forces exerted by its neighbors must be equal in magnitude and opposite in direction. Therefore, the tension has the same value everywhere and is equal to the force that the cord exerts on the objects attached to its ends.

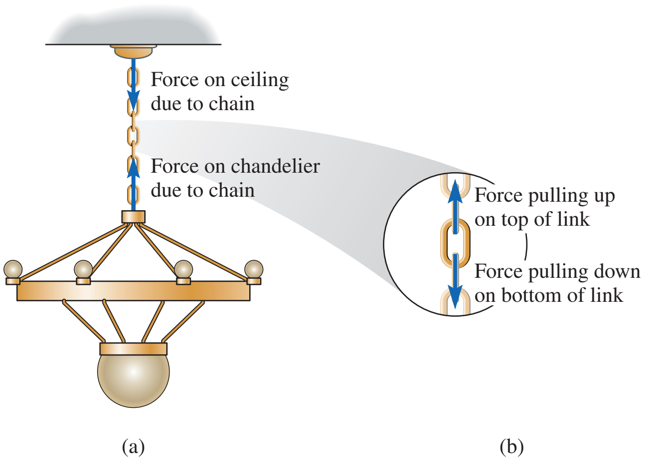


**Figure 2.36** (a) The chain pulls up on the chandelier at one end and pulls down on the ceiling at the other. If the weight of the chain itself is negligibly small, these forces are equal in magnitude, because the net force *on* the chain is zero. The magnitude of these forces is the tension in the chain. (b) The chain is under tension. Each link is pulled in opposite directions by its neighbors.

## Example 2.15

### Archery Practice

Figure 2.37 shows the bowstring of a bow and arrow just before it is released. The archer is pulling back on the midpoint of the bowstring with a horizontal force of 162 N. What is the tension in the bowstring?

**Strategy** Consider a small segment of the bowstring that touches the archer's finger. That piece of the string is in equilibrium, so the net force acting on it is zero. We draw the FBD, choose coordinate axes, and apply the equilibrium condition: $\Sigma F_x = 0$ and $\Sigma F_y = 0$. We know the force exerted on the segment of string by the archer's fingers. That segment is also pulled on each end by the tension in the string. Can we assume the tension in the string is the same everywhere? The weight of the string is small compared to the other forces acting on it. The archer pulls sideways on the bowstring, exerting little or no *tangential* force, so we can assume the tension is the same everywhere.

**Solution** Figure 2.38a is an FBD for the segment of bowstring being considered. The forces are labeled with their magnitudes: $F_a$ for the force applied by the archer's finger and $T$ for each of the tension forces. Figure 2.38b shows these three forces adding to zero. From this sketch, we expect the tension $T$ to be roughly the same as $F_a$. We choose the $x$-axis to the right and the $y$-axis upward. To find the components of the forces due to tension in the string, we draw a triangle (Fig. 2.38c). From the measurements given, we can find the angle $\theta$.

$$\sin\theta = \frac{\text{opposite}}{\text{hypotenuse}} = \frac{35\text{ cm}}{72\text{ cm}} = 0.486$$

$$\theta = \sin^{-1} 0.486 = 29.1°$$

The $x$-component of the tension force exerted on the upper end of the segment is

$$T_x = -T\sin\theta$$

The $x$-component of the force exerted on the lower end of the string is the same. Therefore,

$$\sum F_x = -2T\sin\theta + F_a = 0$$

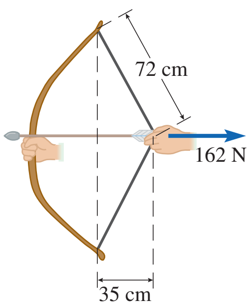


**Figure 2.37**
The force applied to the bowstring by an archer.

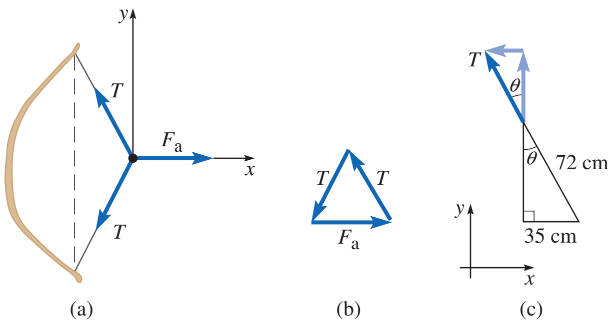


**Figure 2.38**
(a) Free-body diagram for a point on the bowstring with the magnitudes of the forces labeled. (b) Graphical addition of the three forces showing that the sum is zero. (c) The angle $\theta$ is used to find the $x$- and $y$-components of the forces exerted at each end of the bowstring.

Solving for $T$,

$$T = \frac{F_a}{2\sin\theta} = \frac{162\text{ N}}{2\times 0.486} = 170\text{ N}$$

**Discussion** The tension is only slightly larger than $F_a$, a reasonable result given the picture of graphical vector addition in Fig. 2.38b.

In this problem, only the $x$-components of the forces had to be used. The $y$-components must also add to zero. At the upper end of the string, the $y$-component of the force exerted by the bow is $+T\cos\theta$, while at the lower end it is $-T\cos\theta$. Therefore, $\Sigma F_y = 0$.

The expression $T = F_a/(2\sin\theta)$ can be evaluated for limiting values of $\theta$ to make sure that the expression is correct. As $\theta$ approaches 90°, the tension approaches $F_a/(2\sin 90°) = \frac{1}{2}F_a$. That is correct because the archer would be pulling to the right with a force $F_a$, while each side of the bowstring would pull to the left with a force of magnitude $T$. For equilibrium, $F_a = 2T$ or $T = \frac{1}{2}F_a$.

As $\theta$ gets smaller, $\sin\theta$ decreases and the tension increases (for a fixed value of $F_a$). That agrees with our intuition. The larger the tension, the smaller the angle the string needs to make in order to supply the necessary horizontal force.

### Practice Problem 2.15 Tightrope Practice

Jorge decides to rig up a tightrope in the backyard so his children can develop a good sense of balance (Fig. 2.39). For safety reasons, he positions a horizontal cable only 0.60 m above the ground. If the 6.00-m-long cable sags by 0.12 m from its taut horizontal position when Denisha (weight 250 N) is standing on the middle of it, what is the tension in the cable? Ignore the weight of the cable.

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Example 2.15 continued

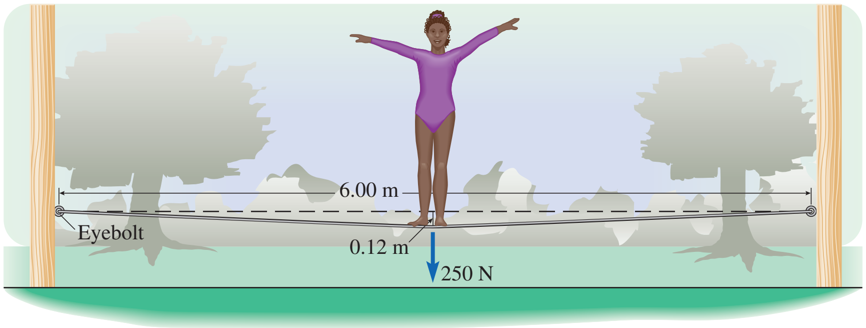



**Figure 2.39**
What is the tension in the cable?

**Application: Tensile Forces in the Body** Tensile forces are central in the study of animal motion. Muscles are usually connected by tendons, one at each end of the muscle, to two different bones, which in turn are linked at a joint (Fig. 2.40). When the muscle contracts, the tension in the tendons increases, pulling on both of the bones.

## EVERYDAY PHYSICS DEMO

Sit with your arm bent at the elbow with a heavy object on the palm of your hand. You can feel the contraction of the biceps muscle. With your other hand, feel the tendon that connects the biceps muscle to your forearm.

Now place your hand palm down on the desktop and push down. Now it is the triceps muscle that contracts, pulling up on the bone on the other side of the elbow joint. Muscles and tendons cannot push; they can only pull. The biceps muscle cannot push the forearm downward, but the triceps muscle can pull on the other side of the joint. In both cases, the arm acts as a lever.

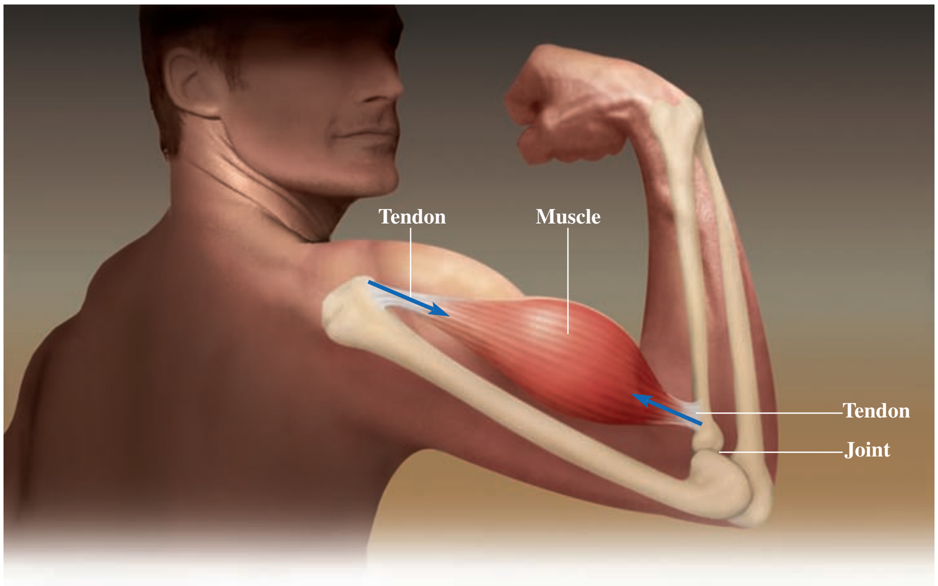



**Figure 2.40** A muscle contracts, increasing the tension in the attached tendons. The tendons exert forces on two different bones.

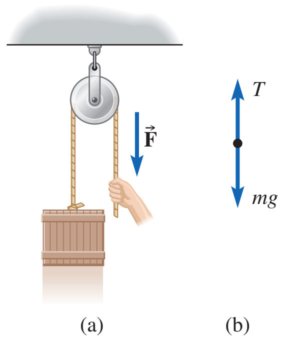



**Figure 2.41** (a) Using a pulley to lift a crate by pulling *downward* on a rope with force $\vec{\mathbf{F}}$. (b) A free-body diagram for the crate. If the crate is in equilibrium, then the tension $T$ must be equal to the weight of the crate $mg$.

**Application: Ideal Pulleys** A pulley can change the direction of the force exerted by a cord under tension. To lift something heavy, it is easier to stand on the ground and pull *down* on the rope than to get above the weight on a platform and pull up on the rope (Fig. 2.41).

An *ideal* pulley has no mass and no friction. An ideal pulley exerts no forces on the cord that are *tangent* to the cord—it is not pulling in either direction along the cord. As a result, the tension of an ideal cord that runs through an ideal pulley is the same on both sides of the pulley. (The proof of this statement comes in Chapter 3.) An ideal pulley changes the direction of the force exerted by a cord without changing its magnitude. As long as a real pulley has a small mass and negligible amount of friction, we can approximate it as an ideal pulley.

Look back at Example 2.4. The "three cords" are actually a single cord wrapped around some pulleys. If these pulleys are ideal, the tension in the cord must be the same everywhere. At its lowest end, the cord holds up a 22.0-N weight. Since the weight is in equlibrium, we know the tension must be 22.0 N.

## Example 2.16

### A Two-Pulley System

A 1804-N engine is hauled upward at constant speed (Fig. 2.42). What are the tensions in the three ropes labeled A, B, and C? Assume the ropes and the pulleys labeled L and R are ideal.

**Strategy** The engine and pulley L move up at constant speed, so the net force on each of them is zero. Pulley R is at rest, so the net force on it is also zero. We can draw the FBD for any or all of these objects and then apply the equilibrium condition. If the pulleys are ideal, the tension in the rope is the same on both sides of the pulley. Therefore, rope C—which is attached to the ceiling—passes around both pulleys, and is pulled downward at the other end, has the same tension throughout. Call the tensions in the three ropes $T_A$, $T_B$, and $T_C$. To analyze the forces exerted on a pulley, we define our system so the part of the rope wrapped around the pulley is considered part of the pulley. Then there are two cords pulling on the pulley, each with the same tension.

**Solution** There are two forces acting on the engine: the gravitational force (1804 N, downward) and the upward pull of rope A. These must be equal and opposite (Fig. 2.43a), since the net force is zero. Therefore $T_A = 1804$ N.

The FBD for pulley L (Fig. 2.43b) shows rope A pulling down with a force of magnitude $T_A$ and rope C pulling upward on *each side*. The rope has the same tension throughout, so all forces labeled $T_C$ in Fig. 2.43b,c have the same magnitude. For the net force to equal zero,

$$2T_C = T_A$$

$$T_C = \frac{1}{2}T_A = 902.0 \text{ N}$$

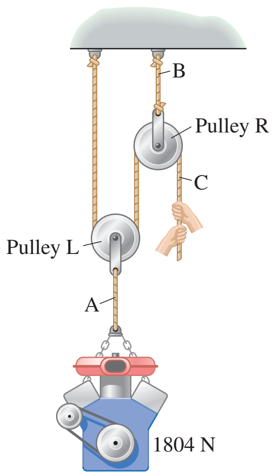



**Figure 2.42**
A system of pulleys used to raise a heavy engine.

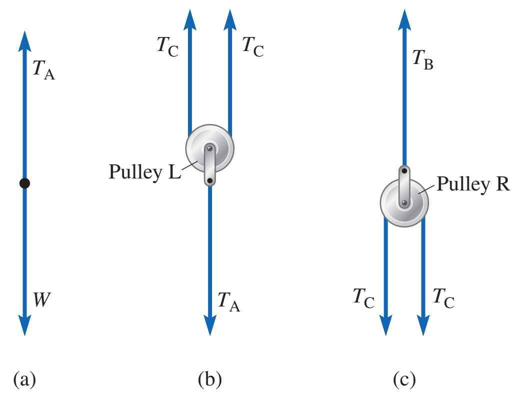



**Figure 2.43**
(a) Free-body diagram for the engine. (b) Free-body diagram for pulley L and (c) FBD for pulley R.

*continued on next page*

Example 2.16 continued

Figure 2.43c is the FBD for pulley R. Rope B pulls upward on it with a force of magnitude $T_B$. On *each side* of the pulley, rope C pulls downward. For the net force to equal zero,

$$T_B = 2T_C = 1804 \text{ N}$$

**Discussion** The engine is raised by pulling *down* on a rope—the pulleys change the direction of the applied force needed to lift the engine. In this case they also change the *magnitude* of the required force. They do that by making the rope pull up on the engine twice, so the person pulling the rope only needs to exert a force equal to half the engine's weight.

**Practice Problem 2.16** System of Ropes, Pulleys, and Engine

Consider the entire collection of ropes, pulleys, and the engine to be a single system. Draw the FBD for this system and show that the net force is zero. [*Hint:* Remember that only forces exerted by objects *external* to the system are included in the FBD.]

## 2.9 FUNDAMENTAL FORCES

One of the main goals of physics has been to understand the immense variety of forces in the universe in terms of the fewest number of fundamental laws. Physics has made great progress in this quest for *unification;* today all forces are understood in terms of just four fundamental interactions (Fig. 2.44). At the high temperatures present in the early universe, two of these interactions—the electromagnetic and weak forces—are now understood as the effects of a single electroweak interaction. The ultimate goal is to describe all forces in terms of a single interaction.

**Gravity** You may be surprised to learn that gravity is by far the *weakest* of the fundamental forces. Any two objects exert gravitational forces on one another, but the force is tiny unless at least one of the masses is large. We tend to notice the relatively large gravitational forces exerted by planets and stars, but not the feeble gravitational forces exerted by smaller objects, such as the gravitational force this book exerts on your body.

Gravity has an unlimited range. The force gets weaker as the distance between two objects increases, but it never drops to zero, no matter how far apart the objects get.

Newton's law of gravity is an early example of unification. Before Newton, people did not understand that the same kind of force that makes an apple fall from a tree also keeps the planets in their orbits around the Sun. A single law—Newton's law of universal gravitation—describes both.

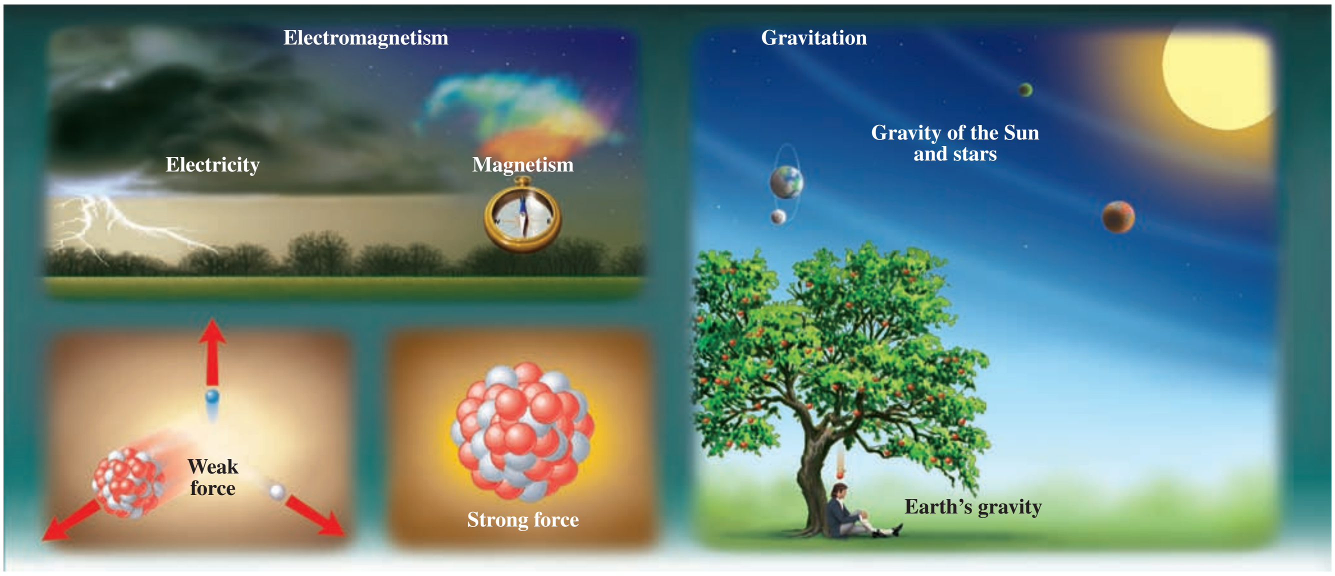



**Figure 2.44** All forces result from just four fundamental forces: gravity, electromagnetism, and the weak and strong forces.

**Electromagnetism** The electromagnetic force is unlimited in range, like gravity. It acts on particles with electric charge. The electric and magnetic forces were unified into a single theoretical framework in the nineteenth century. We study electromagnetic forces in detail in Part 3 of this book.

Electromagnetism is the fundamental interaction that binds electrons to nuclei to form atoms and binds atoms together in molecules and solids. It is responsible for the properties of solids, liquids, and gases and forms the basis of the sciences of chemistry and biology. It is the fundamental interaction behind all macroscopic contact forces such as the frictional and normal forces between surfaces and forces exerted by springs, muscles, and the wind.

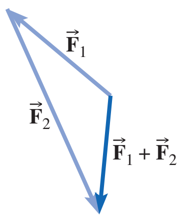
The electromagnetic force is *much* stronger than gravity. For example, the electrical repulsion of two electrons at rest is about $10^{43}$ times as strong as the gravitational attraction between them. Macroscopic objects have a nearly perfect balance of positive and negative electric charge, resulting in a nearly perfect balance of attractive and repulsive electromagnetic forces between the objects. Therefore, despite the fundamental strength of the electromagnetic forces, the net electromagnetic force between two macroscopic objects is often negligibly small except when atoms on the two surfaces come very close to each other—what we think of as *in contact.* On a microscopic level, there is no fundamental difference between contact forces and other electromagnetic forces.

**The Strong Force** The strong force holds protons and neutrons together in the atomic nucleus. The same force binds quarks (a family of elementary particles) in combinations so they can form protons and neutrons and many more exotic subatomic particles. The strong force is the strongest of the four fundamental forces—hence its name—but its range is short: its effect is negligible at distances much larger than the size of an atomic nucleus (about $10^{-15}$ m).

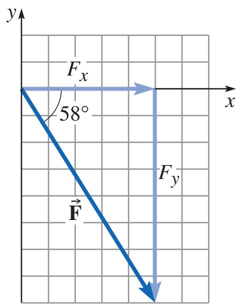
**The Weak Force** The range of the weak force is even shorter than that of the strong force (about $10^{-17}$ m). It is manifest in many radioactive decay processes.

## Master the Concepts

- An interaction between two objects consists of two forces, one on each of the objects. Loosely speaking, a *force* is a push or a pull. Gravity and electromagnetic forces have unlimited range. All other forces exerted on macroscopic objects involve contact. Force is a vector quantity.




- Vectors have magnitude and direction and are added according to special rules. Vectors are added graphically by drawing each vector so that its tail is placed at the tip of the previous vector. The sum is drawn as a vector arrow from the tail of the first vector to the tip of the last.




- To find the components of a vector: draw a right triangle with the vector as the hypotenuse and the other two sides parallel to the *x*- and *y*-axes. Then use the trigonometric functions to find the magnitudes of the components. The correct algebraic sign must be determined for each component. The same triangle can be used to find the magnitude and direction of a vector if its components are known.
- To add vectors algebraically, add their components to find the components of the sum:

$$\text{if } \vec{\mathbf{A}} + \vec{\mathbf{B}} = \vec{\mathbf{C}}, \text{ then } A_x + B_x = C_x \text{ and } A_y + B_y = C_y$$

- The SI unit of force is the newton. 1.00 N = 0.2248 lb.
- The *net force* on a system is the vector sum of all the forces acting on it:

$$\vec{\mathbf{F}}_{\text{net}} = \sum \vec{\mathbf{F}} = \vec{\mathbf{F}}_1 + \vec{\mathbf{F}}_2 + \cdots + \vec{\mathbf{F}}_n \qquad \text{(2-4)}$$

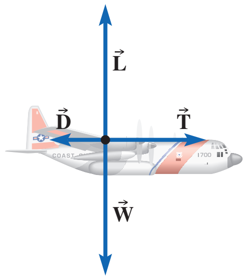
  Since all the internal forces form interaction pairs, we need only sum the external forces.
- *Newton's first law of motion:* If zero net force acts on an object, then the object's velocity does not change. Velocity is a vector whose magnitude is the speed at

*continued on next page*

## Master the Concepts continued

which the object moves and whose direction is the direction of motion.

- A *free-body diagram* (FBD) includes vector arrows representing every force acting on the chosen object due to some other object, but no forces acting on other objects.




- *Newton's third law of motion:* In an interaction between two objects, each object exerts a force on the other. These two forces are equal in magnitude and opposite in direction:

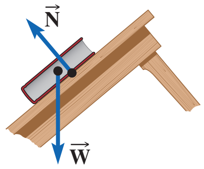
$$\vec{\mathbf{F}} \text{ (on } B \text{ by } A) = -\vec{\mathbf{F}} \text{ (on } A \text{ by } B) \quad \textbf{(2-6)}$$

- At the fundamental level, there are four interactions: gravity, the strong and weak interactions, and the electromagnetic interaction. Contact forces are large-scale manifestations of many microscopic electromagnetic interactions.
- The magnitude of the *gravitational force* between two objects is

$$F = \frac{Gm_1m_2}{r^2} \quad \textbf{(2-7)}$$

where $r$ is the distance between their centers. Each object is pulled toward the other's center.

- The *weight* of an object is the magnitude of the gravitational force acting on it. An object's weight is proportional to its mass: $W = mg$ [Eq. (2-10a)], where $g$ is the gravitational field strength. Near Earth's surface, $g$ has an average value of 9.80 N/kg.
- The *normal force* is a contact force perpendicular to the contact surfaces that pushes each object away from the other.




- *Friction* is a contact force parallel to the contact surfaces. In a simplified model, the kinetic frictional force and the maximum static frictional force are proportional to the normal force acting between the same contact surfaces.

$$f_s \le \mu_s N \quad \textbf{(2-13)}$$

$$f_k = \mu_k N \quad \textbf{(2-14)}$$

The static frictional force acts in the direction that tends to keep the surfaces from beginning to slide. The direction of the kinetic frictional force is in the direction that would tend to make the sliding stop.

- An ideal cord pulls in the direction of the cord with forces of equal magnitude on the objects attached to its ends as long as no external force tangent to the cord is exerted on it anywhere between the ends. The tension of an ideal cord that runs through an ideal pulley is the same on both sides of the pulley.

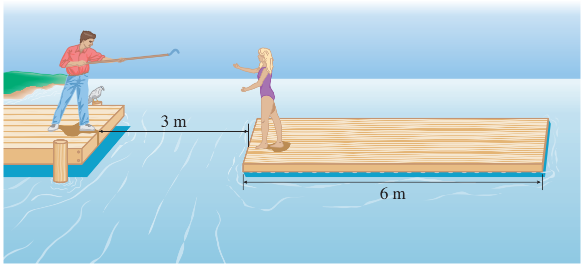
## Conceptual Questions

1. Explain the need for automobile seat belts in terms of Newton's first law.
2. An American visitor to Finland is surprised to see heavy metal frames outside of all the apartment buildings. On Saturday morning the purpose of the frames becomes evident when several apartment dwellers appear, carrying rugs and carpet beaters to each frame. What role does the principle of inertia play in the rug beating process? Do you see a similarity to the role the principle of inertia plays when you throw a baseball?
3. You are lying on the beach after a dip in the ocean where the waves were buffeting you around. Is it true that there are now no forces acting on you? Explain.
4. A dog goes swimming at the beach and then shakes himself all over to get dry. What principle of physics aids in the drying process? Explain.
5. In an attempt to tighten the loosened steel head of a hammer, a carpenter holds the hammer vertically, raises it up, and then brings it down rapidly, hitting the bottom end of the wood handle on a two-by-four board. Explain how this tightens the head back onto the handle.

6. When a car begins to move forward, what force makes it do so? Remember that it has to be an *external* force; the internal forces all add to zero. How does the

engine, which is part of the car, cause an *external* force to act on the car?

7. Two cars are headed toward each other in opposite directions along a narrow country road. The cars collide head-on, crumpling up the hoods of both. Describe what happens to the car bodies in terms of the principle of inertia. Does the rear end of the car stop at the same time as the front end?
8. (a) Is it possible for the sum of two vectors to be smaller in magnitude than the magnitude of either vector? (b) Is it possible for the magnitude of the sum of two vectors to be larger than the sum of the magnitudes of the vectors?
9. (a) What assumptions do you make when you call the reading of a bathroom scale your "weight"? What does the scale really tell you? (b) Under what circumstances might the reading of the scale *not* be equal to your weight?
10. A freight train consists of an engine and several identical cars on level ground. Determine whether each of these statements is correct or incorrect and explain why. (a) If the train is moving at constant speed, the engine must be pulling with a force greater than the train's weight. (b) If the train is moving at constant speed, the engine's pull on the first car must exceed that car's backward pull on the engine. (c) If the train is coasting, its inertia makes it slow down and eventually stop.
11. (a) Does a man weigh more at the North Pole or at the equator? (b) Does he weigh more at the top of Mt. Everest or at the base of the mountain?
12. What is the distinction between a vector and a scalar quantity? Give two examples of each.
13. If a wagon starts at rest and pulls back on you with a force equal to the force you pull on it, as required by Newton's third law, how is it possible for you to make the wagon start to move? Explain.
14. Can the $x$-component of a vector ever be greater than the magnitude of the vector? Explain.
15. A heavy ball hangs from a string attached to a sturdy wooden frame. A second string is attached to a hook on the bottom of the lead ball. You pull slowly and steadily on the lower string. Which string do you think will break first? Explain.
16. An SUV collides with a Mini Cooper convertible. Is the force exerted on the Mini by the SUV greater than, equal to, or less than the force exerted on the SUV by the Mini? Explain.
17. You are standing on one end of a light wooden raft that has floated 3 m away from the pier. If the raft is 6 m long by 2.5 m wide and you are standing on the raft end nearest to the pier, can you propel the raft back toward the pier where a friend is standing with a pole and hook trying to reach you? You have no oars. Make suggestions of what to do without getting yourself wet.



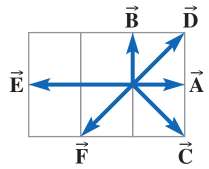

18. If two vectors have the same magnitude, are they necessarily equal? If not, why not? Can two vectors with different magnitudes ever be equal?
19. Compare the advantages and disadvantages of the two methods of vector addition (graphical and algebraic).
20. Pulleys and inclined planes are examples of *simple machines.* Explain what these machines do in Examples 2.4, 2.14, and 2.16 to make a task easier to perform.
21. For a problem about a crate sliding along an inclined plane, is it possible to choose the $x$-axis so that it is parallel to the incline?
22. A bird sits on a stretched clothesline, causing it to sag slightly. Is the tension in the line greatest where the bird sits, greater at either end of the line where it is attached to poles, or the same everywhere along the line? Treat the line as an ideal cord with negligible weight.
23. Does the concept of a contact force apply to both a macroscopic scale and an atomic scale? Explain.

## Multiple-Choice Questions

Student Response System Questions

1. Interaction partners
   (a) are equal in magnitude and opposite in direction and act on the same object.
   (b) are equal in magnitude and opposite in direction and act on different objects.
   (c) appear in an FBD for a given object.
   (d) always involve gravitational force as one partner.
   (e) act in the same direction on the same object.
2. Within a given system, the internal forces
   (a) are always balanced by the external forces.
   (b) all add to zero.
   (c) are determined only by subtracting the external forces from the net force on the system.
   (d) determine the motion of the system.
   (e) can never add to zero.

3. A friction force is
   (a) a contact force that acts parallel to the contact surfaces.
   (b) a contact force that acts perpendicular to the contact surfaces.
   (c) a scalar quantity since it can act in any direction along a surface.
   (d) always proportional to the weight of an object.
   (e) always equal to the normal force between the objects.
4. Your car won't start, so you are pushing it. You apply a horizontal force of 300 N to the car, but it doesn't budge. What force is the interaction partner of the 300-N force you exert?
   (a) the frictional force exerted on the car by the road
   (b) the force exerted on you by the car
   (c) the frictional force exerted on you by the road
   (d) the normal force on you by the road
   (e) the normal force on the car by the road
5. When a force is called a "normal" force, it is
   (a) the usual force expected given the arrangement of a system.
   (b) a force that is perpendicular to the surface of the Earth at any given location.
   (c) a force that is always vertical.
   (d) a contact force perpendicular to the contact surfaces between two solid objects.
   (e) the net force acting on a system.
6. When an object is in translational equilibrium, which of these statements is *not* true?
   (a) The vector sum of the forces acting on the object is zero.
   (b) The object must be stationary.
   (c) The object has a constant velocity.
   (d) The speed of the object is constant.
7. Which of these is *not* a long-range force?
   (a) the force that makes raindrops fall to the ground
   (b) the force that makes a compass point north
   (c) the force that a person exerts on a chair while sitting
   (d) the force that keeps the Moon in its orbital path around the Earth
8. To make an object start moving on a surface with friction requires
   (a) less force than to keep it moving on the surface.
   (b) the same force as to keep it moving on the surface.
   (c) more force than to keep it moving on the surface.
   (d) a force equal to the weight of the object.
9. Vector $\vec{\mathbf{A}}$ in the drawing is equal to
   (a) $\vec{\mathbf{C}} + \vec{\mathbf{D}}$  (b) $\vec{\mathbf{C}} + \vec{\mathbf{D}} + \vec{\mathbf{E}}$  (c) $\vec{\mathbf{C}} + \vec{\mathbf{F}}$
   (d) $\vec{\mathbf{B}} + \vec{\mathbf{C}}$  (e) $\vec{\mathbf{B}} + \vec{\mathbf{F}}$
10. Which vector sum is *not* equal to zero?
    (a) $\vec{\mathbf{C}} + \vec{\mathbf{D}} + \vec{\mathbf{E}}$  (b) $\vec{\mathbf{B}} + \vec{\mathbf{C}} + \vec{\mathbf{F}}$
    (c) $\vec{\mathbf{D}} + \vec{\mathbf{F}}$  (d) $\vec{\mathbf{A}} + \vec{\mathbf{B}} + \vec{\mathbf{F}}$




Multiple-Choice Questions 9 and 10

11. You place two different coins on the cover of your physics book and then slowly lift the cover. Assuming the coefficients of static friction are the same, which is true?
    (a) The more massive coin starts to slide first.
    (b) The less massive coin starts to slide first.
    (c) The two coins start to slide at the same time.
12. A crate containing a new water heater weighs 800 N. The crate rests on the basement floor. Tim pushes horizontally on it with a force of 400 N, but it doesn't budge. What can you conclude about the coefficient of static friction between the crate and the floor?
    (a) $\mu_s = 0.5$
    (b) $\mu_s \geq 0.5$
    (c) $\mu_s \leq 0.5$
    (d) Not enough information is given to draw any of these conclusions.
13. A crate containing a new water heater weighs 800 N. Tim and a friend push horizontally on the water heater with a force of 600 N as it slides across the floor with constant velocity. What can you conclude about the coefficient of kinetic friction between the crate and the floor?
    (a) $\mu_k = 0.75$
    (b) $\mu_k \geq 0.75$
    (c) $\mu_k \leq 0.75$
    (d) Not enough information is given to draw any of these conclusions.
14. A woman stands on an airport's moving sidewalk and moves due west at constant velocity. The frictional force on the woman is ______.
    (a) zero
    (b) kinetic and to the west
    (c) kinetic and to the east
    (d) static and to the west
    (e) static and to the east

***Questions 15–18.*** For each situation, how does the magnitude of the normal force *N* compare with the object's weight *W?* Answer choices:
   (a) equal to *W*
   (b) greater than *W*
   (c) less than *W*
   (d) The given information is insufficient to determine the relative magnitude of the normal force.

15. A child (weight $W$) sits on a level floor. The normal force on the child is _____.
16. A car (weight $W$) is parked on an incline. The magnitude of the normal force on the car is _____.
17. A weightlifter (weight $W$) holds a 400-N barbell above his head. The magnitude of the normal force on the weightlifter due to the floor is _____.
18. A passenger (weight $W$) rides in an elevator. The magnitude of the normal force on the passenger due to the floor is _____.

## Problems

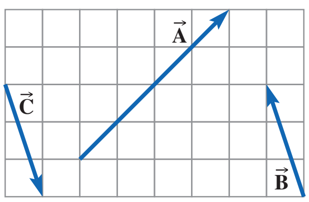
- (C) Combination conceptual/quantitative problem
- Biomedical application
- ✦ Challenging
- Blue # Detailed solution in the Student Solutions Manual
- [1, 2] Problems paired by concept
- connect Text website interactive or tutorial

### 2.1 Force

1. A person is standing on a bathroom scale. Which of the following is *not* a force exerted *on the scale:* a contact force due to the floor, a contact force due to the person's feet, the weight of the person, the weight of the scale?
2. Which item/s in the following list is/are a vector quantity? volume, force, speed, length, time
3. Which item in the following list is *not* a scalar? temperature, test score, stock value, humidity, velocity, mass
4. A sack of flour has a weight of 19.8 N. What is its weight in pounds?
5. An astronaut weighs 175 lb. What is his weight in newtons?

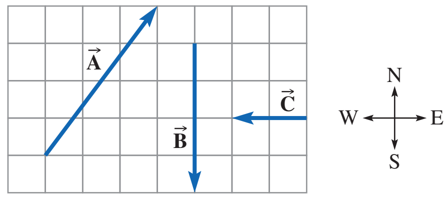
### 2.2 Graphical Vector Addition

6. Rank the vectors $\vec{\mathbf{A}}$, $\vec{\mathbf{B}}$, and $\vec{\mathbf{C}}$ in order of increasing magnitude. Explain your reasoning.



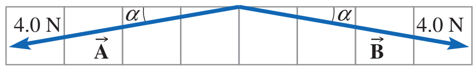

Problems 6, 7, and 16

7. Vectors $\vec{\mathbf{A}}$, $\vec{\mathbf{B}}$, and $\vec{\mathbf{C}}$ are shown in the figure. (a) Draw vectors $\vec{\mathbf{D}}$ and $\vec{\mathbf{E}}$, where $\vec{\mathbf{D}} = \vec{\mathbf{A}} + \vec{\mathbf{B}}$ and $\vec{\mathbf{E}} = \vec{\mathbf{A}} + \vec{\mathbf{C}}$. (b) Show that $\vec{\mathbf{A}} + \vec{\mathbf{B}} = \vec{\mathbf{B}} + \vec{\mathbf{A}}$ by graphical means.
8. In the drawing, what is the vector sum of forces $\vec{\mathbf{A}} + \vec{\mathbf{B}} + \vec{\mathbf{C}}$ if each grid square is 2 N on a side?



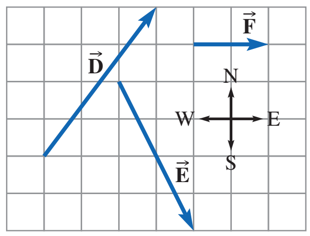

Problems 8, 14, and 19

9. Two vectors, each of magnitude 4.0 N, are inclined at a small angle $\alpha$ below the horizontal, as shown. Let $\vec{\mathbf{C}} = \vec{\mathbf{A}} + \vec{\mathbf{B}}$. Sketch the direction of $\vec{\mathbf{C}}$ and estimate its magnitude. (The grid is 1 N on a side.)




Problems 9 and 18

10. In the drawing, what is the vector sum of forces $\vec{\mathbf{D}} + \vec{\mathbf{E}} + \vec{\mathbf{F}}$ if each grid square is 2 N on a side?




Problems 10, 11, 15, and 20

11. Rank the vectors $\vec{\mathbf{D}}$, $\vec{\mathbf{E}}$, and $\vec{\mathbf{F}}$ in order of increasing magnitude. Explain your reasoning.
12. Two of Robin Hood's men are pulling a sledge loaded with some gold along a path that runs due north to their hideout. One man pulls his rope with a force of 62 N at an angle of 12° east of north and the other pulls with the same force at an angle of 12° west of north. Use the graphical method to find the sum of these two forces on the sledge. Assume the ropes are parallel to the ground.
13. Juan is helping his mother rearrange the living room furniture. Juan pushes on the armchair with a force of 30 N directed at an angle of 15° above a horizontal line while his mother pushes with a force of 40 N directed at an angle of 20° below the same horizontal. What is the vector sum of these two forces? Use graph paper, ruler, and protractor to find a graphical solution.

### 2.3 Vector Addition Using Components

14. Rank vectors $\vec{\mathbf{A}}$, $\vec{\mathbf{B}}$, and $\vec{\mathbf{C}}$ in Problem 8 in order of increasing $x$-component if the $x$-axis points east. Explain your reasoning.

15. Rank vectors $\vec{\mathbf{D}}$, $\vec{\mathbf{E}}$, and $\vec{\mathbf{F}}$ in Problem 10 in order of increasing $y$-component if the $y$-axis points north. Explain your reasoning.

16. Rank, in order of increasing $x$-component, $\vec{\mathbf{A}}+\vec{\mathbf{B}}$, $\vec{\mathbf{B}}+\vec{\mathbf{C}}$, and $\vec{\mathbf{A}}+\vec{\mathbf{C}}$ in Problem 7. The $x$-axis points to the right. Explain your reasoning.

17. A force of 20 N is directed at an angle of 60° above the $x$-axis. A second force of 20 N is directed at an angle of 60° below the $x$-axis. What is the vector sum of these two forces? Use graph paper to find your answer.

18. In Problem 9, let $\alpha = 10°$ and find the magnitude of vector $\vec{\mathbf{C}}$ using the component method.

19. In Problem 8, use the component method to find the vector sum $\vec{\mathbf{A}}+\vec{\mathbf{B}}+\vec{\mathbf{C}}$. Each grid square is 2 N on a side.

20. In Problem 10, use the component method to find the vector sum $\vec{\mathbf{D}}+\vec{\mathbf{E}}+\vec{\mathbf{F}}$.

21. The velocity vector of a sprinting cheetah has $x$- and $y$-components $v_x = +16.4$ m/s and $v_y = -26.3$ m/s. (a) What is the magnitude of the velocity vector? (b) What angle does the velocity vector make with the $+x$- and $-y$-axes?

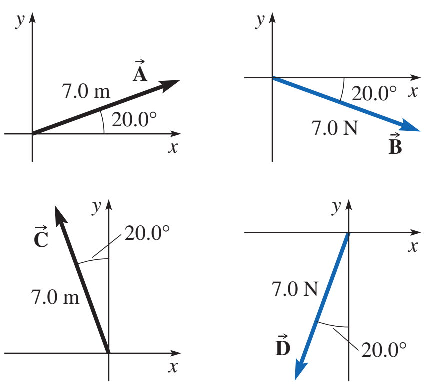
22. A vector is 20.0 m long and makes an angle of 60.0° counterclockwise from the $y$-axis (on the side of the $-x$-axis). What are the $x$- and $y$-components of this vector?

23. Vector $\vec{\mathbf{A}}$ has magnitude 4.0 units; vector $\vec{\mathbf{B}}$ has magnitude 6.0 units. The angle between $\vec{\mathbf{A}}$ and $\vec{\mathbf{B}}$ is 60.0°. What is the magnitude of $\vec{\mathbf{A}}+\vec{\mathbf{B}}$?

24. Vector $\vec{\mathbf{A}}$ is directed along the positive $y$-axis and has magnitude $\sqrt{3.0}$ units. Vector $\vec{\mathbf{B}}$ is directed along the negative $x$-axis and has magnitude 1.0 unit. What are the magnitude and direction of $\vec{\mathbf{A}}+\vec{\mathbf{B}}$?

25. Vector $\vec{\mathbf{a}}$ has components $a_x = -3.0$ m/s$^2$ and $a_y = +4.0$ m/s$^2$. (a) What is the magnitude of $\vec{\mathbf{a}}$? (b) What is the direction of $\vec{\mathbf{a}}$? Give an angle with respect to one of the coordinate axes.

26. Find the $x$- and $y$-components of the four vectors shown in the drawing.




Problems 26–28

27. Suppose the vector $\vec{\mathbf{B}}$ is doubled in magnitude without changing its direction. What happens to its $x$- and $y$-components? Explain your reasoning.

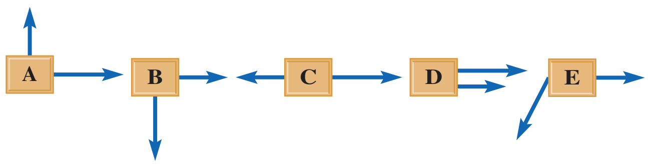
28. Sketch a vector that has the same $y$-component as $\vec{\mathbf{B}}$ but with an $x$-component that is reversed in sign.

29. In each of these, the $x$- and $y$-components of a vector are given. Find the magnitude and direction of the vector. (a) $x = -5.0$ cm, $y = +8.0$ cm. (b) $F_x = +120$ N, $F_y = -60.0$ N. (c) $v_x = -13.7$ m/s, $v_y = -8.8$ m/s. (d) $a_x = 2.3$ m/s$^2$, $a_y = 6.5$ cm/s$^2$.

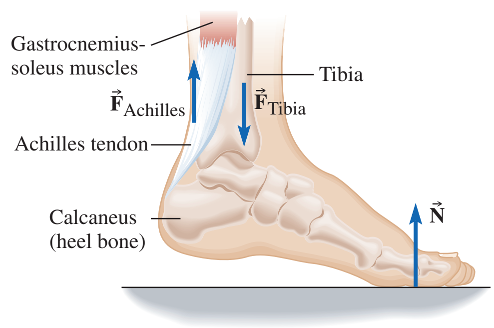
30. Vector $\vec{\mathbf{b}}$ has magnitude 7.1 and direction 14° below the $+x$-axis. Vector $\vec{\mathbf{c}}$ has $x$-component $c_x = -1.8$ and $y$-component $c_y = -6.7$. Compute (a) the $x$- and $y$-components of $\vec{\mathbf{b}}$; (b) the magnitude and direction of $\vec{\mathbf{c}}$; (c) the magnitude and direction of $\vec{\mathbf{c}}+\vec{\mathbf{b}}$.

## 2.4 Inertia and Equilibrium: Newton's First Law of Motion

31. Forces of magnitudes 2000 N and 3000 N act on five objects. The directions of the forces are shown in the sketches. Rank the objects according to the magnitude of the net force, from smallest to largest. Explain your reasoning.




32. A person stands on the ball of one foot. The normal force due to the ground pushing up on the ball of the foot has magnitude 750 N. Ignoring the weight of the foot itself, the other significant forces acting on the foot are the tension in the Achilles tendon pulling up and the force of the tibia pushing down on the ankle joint. If the tension in the Achilles tendon is 2230 N, what is the force exerted on the foot by the tibia?




33. A man is lazily floating on an air mattress in a swimming pool. If the weight of the man and air mattress

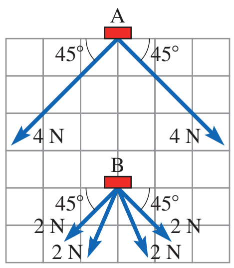
together is 806 N, what is the upward force of the water acting on the mattress?

34. A car is driving on a straight, level road at constant speed. Draw an FBD for the car, showing the significant forces that act on it.

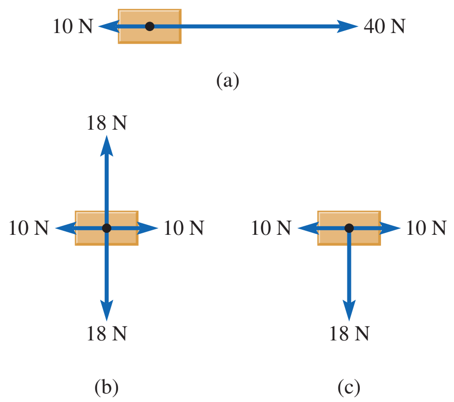
35. A sailboat, tied to a mooring with a line, weighs 820 N. The mooring line pulls horizontally toward the west on the sailboat with a force of 110 N. The sails are stowed away and the wind blows from the west. The boat is moored on a still lake—no water currents push on it. Draw a free-body diagram for the sailboat and indicate the magnitude of each force.

36. A parked automobile slips out of gear, rolls unattended down a slight incline, and then along a level road until it hits a stone wall. Draw an FBD to show the forces acting on the car while it is in contact with the wall.

37. Two objects, A and B, are acted on by the forces shown in the FBDs. Is the magnitude of the net force acting on object B greater than, less than, or equal to the magnitude of the net force acting on object A? Explain.




38. Find the magnitude and direction of the net force on the object in each of the FBDs for this problem.




39. A truck driving on a level highway is acted on by the following forces: a downward gravitational force of 52 kN (kilonewtons); an upward contact force due to the road of 52 kN; another contact force due to the road of 7 kN, directed east; and a drag force due to air resistance of 5 kN, directed west. What is the net force acting on the truck?

40. Two forces of magnitudes 3.0 N and 4.0 N act on an object. How are the directions of the two forces related if (a) the net force has magnitude 7.0 N or (b) the net force has magnitude 5.0 N? (c) What relationship between the directions gives the smallest magnitude net force, and what is this magnitude?

41. A barge is hauled along a straight-line section of canal by two horses harnessed to tow ropes and walking along the tow paths on either side of the canal. Each horse pulls with a force of 560 N at an angle of 15° with the centerline of the canal. Find the sum of these two forces on the barge. Is this sum the net force on the barge? Explain.

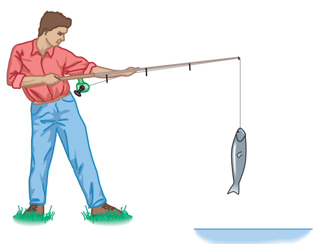
42. On her way to visit Grandmother, Red Riding Hood sat down to rest and placed her 1.2-kg basket of goodies beside her. A wolf came along, spotted the basket, and began to pull on the handle with a force of 6.4 N at an angle of 25° with respect to vertical. Red was not going to let go easily, so she pulled on the handle with a force of 12 N. If the net force on the basket is straight up, at what angle was Red Riding Hood pulling?

## 2.5 Interaction Pairs: Newton's Third Law of Motion

43. A towline is attached between a car and a glider. As the car speeds due east along the runway, the towline exerts a horizontal force of 850 N on the glider. What is the magnitude and direction of the force exerted by the glider on the towline?

44. A hummingbird is hovering motionless beside a flower. The blur of its wings shows that they are rapidly beating up and down. If the air pushes upward on the bird with a force of 0.30 N, what is the force exerted on the air by the hummingbird?

45. A fish is suspended by a line from a fishing rod. Identify the forces acting on the fish and describe the interaction partner of each.



Problems 45 and 46

46. A fisherman is holding a fishing rod with a large fish suspended from the line of the rod. Identify the forces acting on the rod and their interaction partners.

47. Margie, who weighs 543 N, is standing on a bathroom scale that weighs 45 N. (a) With what force does the scale push up on Margie? (b) What is the interaction partner of that force? (c) With what force does the floor push up on the scale? (d) Identify the interaction partner of that force.

48. A bike is hanging from a hook in a garage. Consider the following forces: (a) the force of the Earth pulling down on the bike, (b) the force of the bike pulling up on the Earth, and (c) the force of the hook pulling up on the bike. (a) Which two forces are equal and opposite because of Newton's third law? (b) Which two forces are equal and opposite because of Newton's *first* law? Explain.

***Problems 49–51.*** A skydiver, who weighs 650 N, is falling at a constant speed with his parachute open. Consider the apparatus that connects the parachute to the skydiver to be part of the parachute. The parachute pulls upward on the skydiver with a force of 620 N.

49. (a) Identify the forces acting on the skydiver. Describe each force as: *(type of force)* exerted on *(object 1)* by *(object 2)*. (b) Draw an FBD for the skydiver. (c) Find the magnitude of the force on the skydiver due to the air. (d) Identify the interaction partner for each force acting on the skydiver. For each interaction partner, describe it as *(type of force)* exerted on *(object 1)* by *(object 2)* and determine its magnitude and direction.

50. In Problem 49, (a) identify the forces acting on the parachute. Describe each force as: *(type of force)* exerted on *(object 1)* by *(object 2)*. (b) Draw an FBD for the parachute. (c) What are the magnitude and direction of the force on the parachute due to the skydiver? (d) Identify the interaction partner for each force acting on the parachute. For each interaction partner, describe it as *(type of force)* exerted on *(object 1)* by *(object 2)*.

51. Refer to Problem 49. Consider the skydiver and parachute to be a single system. Identify the external forces acting on this system and draw an FBD.

52. A hanging potted plant is suspended by a cord from a hook in the ceiling. Draw an FBD for each of these: (a) the system consisting of plant, soil, and pot; (b) the cord; (c) the hook; (d) the system consisting of plant, soil, pot, cord, and hook. Label each force arrow using subscripts (e.g., $\vec{\mathbf{F}}_{ch}$ would represent the force exerted on the cord by the hook).

53. A woman who weighs 600 N sits on a chair with her feet on the floor and her arms resting on the chair's armrests. The chair weighs 100 N. Each armrest exerts an upward force of 25 N on her arms. The seat of the chair exerts an upward force of 500 N. (a) What force does the floor exert on her feet? (b) What force does the floor exert on the chair? (c) Consider the woman and the chair to be a single system. Draw an FBD for this system that includes only the *external* forces acting on it.

## 2.6 Gravitational Forces

54. (a) Calculate your weight in newtons. (b) What is the weight in newtons of 250 g of cheese? (c) Name a common object whose weight is about 1 N.

55. A young South African girl has a mass of 40.0 kg. (a) What is her weight in newtons? (b) If she came to the United States, what would her weight be in pounds as measured on an American scale? Assume $g = 9.80$ N/kg in both locations.

56. A man weighs 0.80 kN on Earth. What is his mass in kilograms?

57. Using the information in the opening paragraphs of this chapter, what is the approximate magnitude of the gravitational force between the Earth and the *Voyager* 1 spacecraft? The spacecraft has a mass of approximately 825 kg during the mission, although the mass at launch was 2100 kg because of expendable Titan-Centaur rockets.

58. Find the altitudes above the Earth's surface where Earth's gravitational field strength would be (a) two-thirds and (b) one-third of its value at the surface. [*Hint:* First find the radius for each situation; then recall that the altitude is the distance from the *surface* to a point above the surface. Use proportional reasoning.]

59. Find and compare the weight of a 65-kg man on Earth with the weight of the same man on (a) Mars, where $g = 3.7$ N/kg; (b) Venus, where $g = 8.9$ N/kg; and (c) Earth's Moon, where $g = 1.6$ N/kg.

60. At what altitude above the Earth's surface would your weight be half of what it is at the Earth's surface?

61. During a balloon ascension, wearing an oxygen mask, you measure the weight of a calibrated 5.00-kg mass and find that the value of the gravitational field strength at your location is 9.792 N/kg. How high above sea level, where the gravitational field strength was measured to be 9.803 N/kg, are you located?

62. How far above the surface of the Earth does an object have to be in order for it to have the same weight as it would have on the surface of the Moon? (Ignore any effects from the Earth's gravity for the object on the Moon's surface or from the Moon's gravity for the object above the Earth.)

63. An astronaut stands at a position on the Moon such that Earth is directly over head and releases a Moon

rock that was in her hand. (a) Which way will it fall? (b) What is the gravitational force exerted by the Moon on a 1.0-kg rock resting on the Moon's surface? (c) What is the gravitational force exerted by the Earth on the same 1.0-kg rock resting on the surface of the Moon? (d) What is the net gravitational force on the rock?

64. (a) What is the magnitude of the gravitational force that the Earth exerts on the Moon? (b) What is the magnitude of the gravitational force that the Moon exerts on the Earth? See the inside front and back covers for necessary information.

65. The Space Shuttle carries a satellite in its cargo bay and places it into orbit around the Earth. Find the ratio of the Earth's gravitational force on the satellite when it is on a launch pad at the Kennedy Space Center to the gravitational force exerted when the satellite is orbiting $6.00 \times 10^3$ km above the launch pad.

66. Using the masses and mean distances found on the inside back cover, calculate the net gravitational force on the Moon (a) during a lunar eclipse (Earth between Moon and Sun) and (b) during a solar eclipse (Moon between Earth and Sun).

## 2.7 Contact Forces

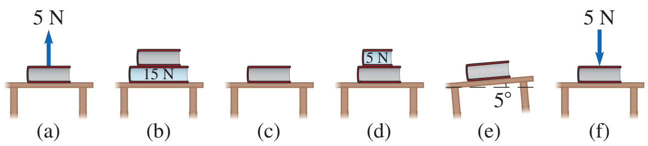
67. A book rests on the surface of the table. Consider the following four forces that arise in this situation: (a) the force of the Earth pulling on the book, (b) the force of the table pushing on the book, (c) the force of the book pushing on the table, and (d) the force of the book pulling on the Earth. The book is not moving. Which pair of forces must be equal in magnitude and opposite in direction even though they are *not* an interaction pair? Explain.

68. Fernando places a 2.0-kg dictionary on a tabletop, then sits on top of the dictionary. Fernando has a mass of 52 kg. (a) What is the normal force exerted by the table on the dictionary? (b) What is the normal force exerted by the dictionary on Fernando? (c) Is there a normal force exerted by the table on Fernando? If so, what is its magnitude?

69. You grab a book and give it a quick push across the top of a horizontal table. After a short push, the book slides across the table, and because of friction, comes to a stop. (a) Draw an FBD of the book while you are pushing it. (b) Draw an FBD of the book after you have stopped pushing it, while it is sliding across the table. (c) Draw an FBD of the book after it has stopped sliding. (d) In which of the preceding cases is the net force on the book not equal to zero? (e) If the book has a mass of 0.50 kg and the coefficient of friction between the book and the table is 0.40, what is the net force acting on the book in part (b)? (f) If there were no friction between the table and the book, what would the FBD for part (b) look like? Would the book slow down in this case? Why or why not?

70. ✦ A box sits on a horizontal wooden ramp. The coefficient of static friction between the box and the ramp is 0.30. You grab one end of the ramp and lift it up, keeping the other end of the ramp on the ground. What is the angle between the ramp and the horizontal direction when the box begins to slide down the ramp? (connect tutorial: crate on ramp)

71. A book that weighs 10 N is at rest in six different situations. Rank the situations according to the magnitude of the normal force on the book *due to the table,* from smallest to greatest. Explain your reasoning.




***Problems 72–75.*** A crate of potatoes of mass 18.0 kg is on a ramp with angle of incline 30° to the horizontal. The coefficients of friction are $\mu_s = 0.75$ and $\mu_k = 0.40$. Find the normal force (magnitude) and the frictional force (magnitude and direction) on the crate if

72. the crate is at rest.

73. the crate is sliding down the ramp.

74. the crate is sliding *up* the ramp.

75. the crate is being carried up the ramp at constant velocity by a conveyor belt (without sliding).

76. A crate full of artichokes is on a ramp that is inclined 10.0° above the horizontal. Give the direction of the normal force and the friction force acting on the crate in each of these situations. (a) The crate is at rest. (b) The crate is sliding up the ramp. (c) The crate is sliding down the ramp.

77. ✦ A 3.0-kg block is at rest on a horizontal floor. If you push horizontally on the 3.0-kg block with a force of 12.0 N, it just starts to move. (a) What is the coefficient of static friction? (b) A 7.0-kg block is stacked on top of the 3.0-kg block. What is the magnitude $F$ of the force, acting horizontally on the 3.0-kg block as before, that is required to make the two blocks start to move?

78. A horse is trotting along pulling a sleigh through the snow. To move the sleigh, of mass $m$, straight ahead at a constant speed, the horse must pull with a force of

magnitude *T*. (a) What is the net force acting on the sleigh? (b) What is the coefficient of kinetic friction between the sleigh and the snow?

79. ✦ Before hanging new William Morris wallpaper in her bedroom, Brenda sanded the walls lightly to smooth out some irregularities on the surface. The sanding block weighs 2.0 N and Brenda pushes on it with a force of 3.0 N at an angle of 30.0° with respect to the vertical, and angled toward the wall. Draw an FBD for the sanding block as it moves straight up the wall at a constant speed. What is the coefficient of kinetic friction between the wall and the block?

80. Four separate blocks are placed side by side in a left-to-right row on a table. A horizontal force, acting toward the right, is applied to the block on the far left end of the row. Draw FBDs for (a) the second block on the left and for (b) the system of four blocks.

81. A conveyor belt carries apples up an incline to a cider press. The apples neither slide nor roll as they move up the incline. (a) Does the belt exert a *static* or *kinetic* frictional force on an apple? Explain. (b) If the normal and frictional forces exerted on an apple have magnitudes 1.0 N and 0.40 N, respectively, what (if anything) can you conclude about the static and kinetic coefficients of friction?

82. (a) In Example 2.14, if the movers stop pushing on the safe, can static friction hold the safe in place without having it slide back down? (b) If not, what minimum force needs to be applied to hold the safe in place?

83. Mechanical advantage is the ratio of the force required without the use of a simple machine to that needed when using the simple machine. Compare the force to lift an object with that needed to slide the same object up a frictionless incline and show that the mechanical advantage of the inclined plane is the length of the incline divided by the height of the incline ($d/h$ in Fig. 2.32).

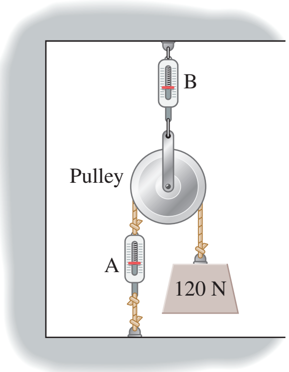
84. An 80.0-N crate of apples sits at rest on a ramp that runs from the ground to the bed of a truck. The ramp is inclined at 20.0° to the ground. (a) What is the normal force exerted on the crate by the ramp? (b) The interaction partner of this normal force has what magnitude and direction? It is exerted *by* what object *on* what object? Is it a contact or a long-range force? (c) What is the static frictional force exerted on the crate by the ramp? (d) What is the minimum possible value of the coefficient of static friction? (e) The normal and frictional forces are perpendicular components of the contact force exerted on the crate by the ramp. Find the magnitude and direction of the contact force.

85. An 85-kg skier is sliding down a ski slope at a constant velocity. The slope makes an angle of 11° above the horizontal direction. (a) Ignoring any air resistance, what is the force of kinetic friction acting on the skier? (b) What is the coefficient of kinetic friction between the skis and the snow?

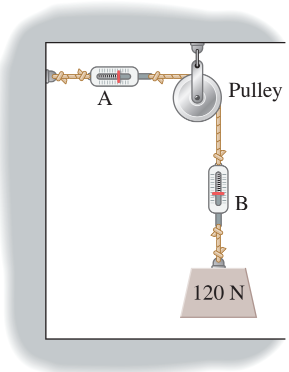
86. You are pulling a suitcase through the airport at a constant speed by exerting a force of 25.0 N at angle 30.0° from the vertical. What is the force of friction acting on the suitcase?

## 2.8 Tension

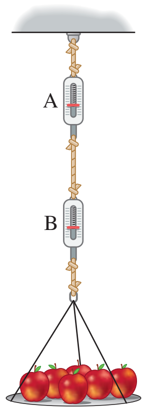
87. Spring scale A is attached to the floor and a rope runs vertically upward, loops over the pulley, and runs down on the other side to a 120-N weight. Scale B is attached to the ceiling and the pulley is hung below it. What are the readings of the two spring scales, A and B? Ignore the weights of the pulley and scales.




88. A pulley is attached to the ceiling. Spring scale A is attached to the wall and a rope runs horizontally from it and over the pulley. The same rope is then attached to spring scale B. On the other side of scale B hangs a 120-N weight. What are the readings of the two scales A and B? The weights of the scales are negligible.

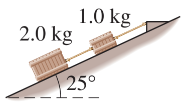


89. A cord, with a spring balance to measure forces attached midway along, is hanging from a hook attached to the ceiling. A mass of 10 kg is hanging from the lower end of the cord. The spring balance indicates a reading of 98 N for the force. Then two people hold the opposite ends of the same cord and pull against each other horizontally until the balance in the middle again reads 98 N. With what force must each person pull to attain this result?

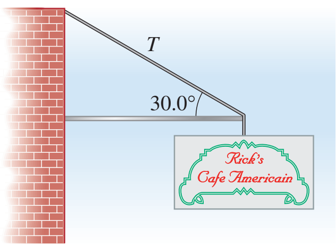



90. Two springs are connected in series so that spring scale A hangs from a hook on the ceiling and a second spring scale, B, hangs from the hook at the bottom of scale A. Apples weighing 120 N hang from the hook at the bottom of scale B. What are the readings on the upper scale A and the lower scale B? Ignore the weights of the scales.

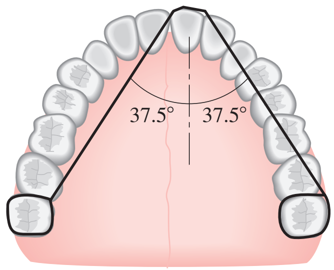
91. Two boxes with different masses are tied together on a frictionless ramp surface. What is the tension in each of the cords?



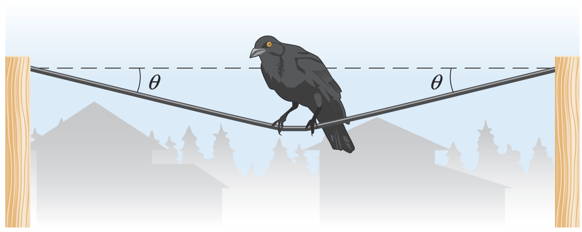

92. A 200.0-N sign is suspended from a horizontal strut of negligible weight. The force exerted on the strut by the wall is horizontal. Draw an FBD to show the forces acting on the strut. Find the tension $T$ in the diagonal cable supporting the strut.



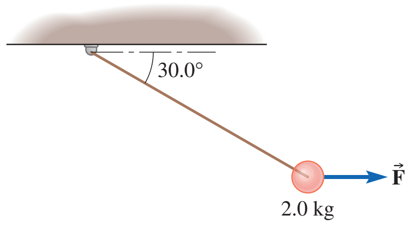

93. ✦ The drawing shows an elastic cord attached to two back teeth and stretched across a front tooth. The purpose of this arrangement is to apply a force $\vec{\mathbf{F}}$ to the front tooth. (The figure has been simplified by drawing the cord as if it ran straight from the front tooth to the back teeth.) If the tension in the cord is 12 N, what are the magnitude and direction of the force $\vec{\mathbf{F}}$ applied to the front tooth?




94. ✦ A crow perches on a clothesline midway between two poles. Each end of the rope makes an angle of $\theta$ below the horizontal where it connects to the pole. If the weight of the crow is $W$, what is the tension in the rope? Ignore the weight of the rope.



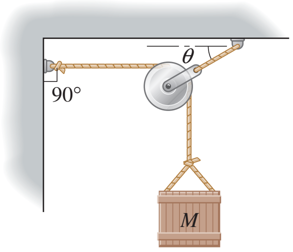

95. A 2.0-kg ball tied to a string fixed to the ceiling is pulled to one side by a force $\vec{\mathbf{F}}$. Just before the ball is released and allowed to swing back and forth, (a) how large is the force $\vec{\mathbf{F}}$ that is holding the ball in position and (b) what is the tension in the string?




96. A 45-N lithograph is supported by two wires. One wire makes a 25° angle with the vertical and the other makes a 15° angle with the vertical. Find the tension in each wire. (connect tutorial: hanging picture)

97. A pulley is hung from the ceiling by a rope. A block of mass $M$ is suspended by another rope that passes over the pulley and is attached to the wall. The rope fastened to the wall makes a right angle with the wall. Ignore the masses

of the rope and the pulley. Find (a) the tension in the rope from which the pulley hangs and (b) the angle $\theta$ that the rope makes with the ceiling.




## 2.9 Fundamental Forces

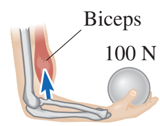
98. Which of the fundamental forces governs the motion of planets in the solar system? Is this the strongest or the weakest of the fundamental forces? Explain.
99. Which of the following forces have an unlimited range: strong force, contact force, electromagnetic force, gravitational force?
100. Which of the following forces bind electrons to nuclei to form atoms: strong force, contact force, electromagnetic force, gravitational force?
101. Which of the fundamental forces has the shortest range, yet is responsible for producing the sunlight that reaches Earth?
102. Which of the fundamental forces binds quarks together to form protons, neutrons, and many exotic subatomic particles?

## Collaborative Problems

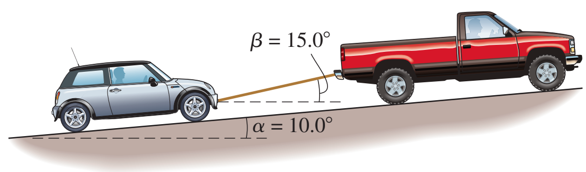
103. A box containing a new TV weighs 350 N. Phineas is pushing horizontally on it with a force of 150 N, but it doesn't budge. (a) Identify all the forces acting on the crate. Describe each as: *(type of force)* exerted on the crate by *(object)*. (b) Identify the interaction partner of each force acting on the crate. Describe each partner as: *(type of force)* exerted on *(object)* by *(object)*. (c) Draw an FBD for the crate. Are any of the interaction partners identified in (b) shown on the FBD? (d) What is the *net* force acting on the crate? Use your answer to determine the magnitude of all the forces acting on the crate. (e) If there are pairs of forces on the FBD that are equal in magnitude and opposite in direction, are these *interaction pairs?* Explain.
104. ✦ You want to hang a 15-N picture as in the figure (a) using some very fine twine that will break with more than 12 N of tension. Can you do this? What if you have it as illustrated in Figure (b)?


(a) (b)

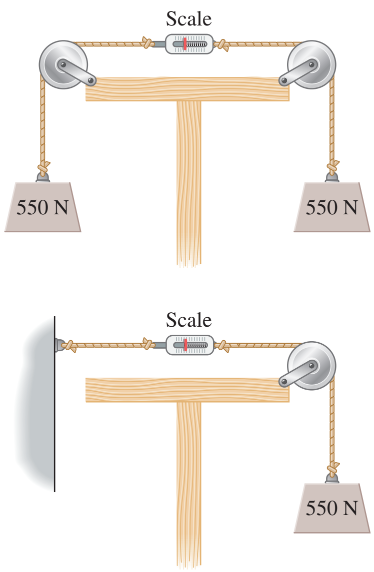
105. ✦ The coefficient of static friction between block A and a horizontal floor is 0.45, and the coefficient of static friction between block B and the floor is 0.30. The mass of each block is 2.0 kg, and they are connected together by a cord. (a) If a horizontal force $\vec{\mathbf{F}}$ pulling on block B is slowly increased, in a direction parallel to the connecting cord, until it is barely enough to make the two blocks start moving, what is the magnitude of $\vec{\mathbf{F}}$ at the instant that they start to slide? (b) What is the tension in the cord connecting blocks A and B at that same instant?
106. When you hold up a 100-N weight in your hand, with your forearm horizontal and your palm up, the upward force exerted by your biceps is much larger than 100 N—perhaps as much as 1000 N. How can that be? What other forces are acting on your forearm? Draw an FBD for the forearm, showing all of the forces. Assume that all the forces exerted on the forearm are purely vertical—either up or down.



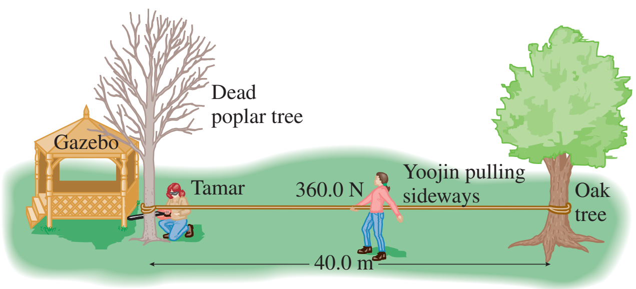

107. A truck is towing a 1250-kg car at a constant speed up a hill that makes an angle of $\alpha = 10.0°$ with respect to the horizontal. A rope is attached from the truck to the car at an angle of $\beta = 15.0°$ with respect to horizontal. Ignore friction on the car in this problem. (a) Draw an FBD showing all the forces on the car. (b) What choice of *x*- and *y*-axes will make it easiest to find the tension in the rope? Explain. (c) Find the tension.



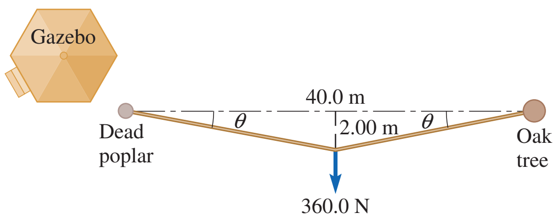

108. The readings of the two spring scales shown in the drawing are the same. (a) Explain why they are the same. [*Hint:* Draw FBDs.] (b) What is the reading?




109. ✦ Ⓒ Tamar wants to cut down a dead poplar tree with her chain saw, but she does not want it to fall onto the nearby gazebo. Yoojin, a physicist, suggests they tie a rope taut from the poplar to the oak tree and then pull *sideways* on the rope as shown in the figure. If the rope is 40.0 m long and Yoojin pulls sideways at the midpoint of the rope with a force of 360.0 N, causing a 2.00-m sideways displacement of the rope at its midpoint, what force will the rope exert on the poplar tree? Compare this with pulling the rope directly away from the poplar with a force of 360.0 N and explain why the values are different. [*Hint:* Until the poplar is cut through enough to start falling, the rope is in equilibrium.]

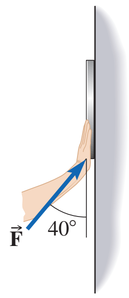


Side view



Overhead view

110. ✦ Ⓒ While trying to decide where to hang a framed picture, you press it against the wall to keep it from falling. The picture weighs 5.0 N, and you press against the frame with a force of 6.0 N at an angle of 40° from the vertical. (a) What is the direction of the normal force exerted on the picture by your hand? (b) What is the direction of the normal force exerted on the picture by the wall? (c) What is the coefficient of static friction between the wall and the picture? The frictional force exerted on the picture by the wall can have two possible directions. Explain why.



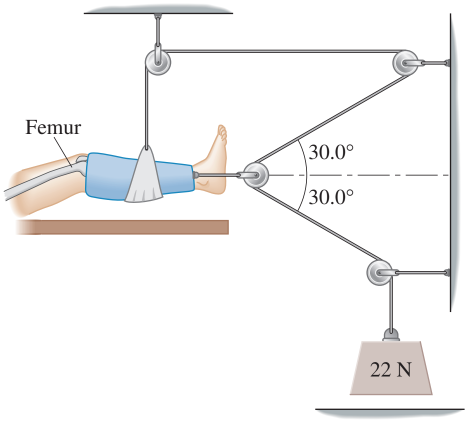

## Comprehensive Problems

111. You want to push a 65-kg box up a 25° ramp. The coefficient of kinetic friction between the ramp and the box is 0.30. With what magnitude force parallel to the ramp should you push on the box so that it moves up the ramp at a constant speed?

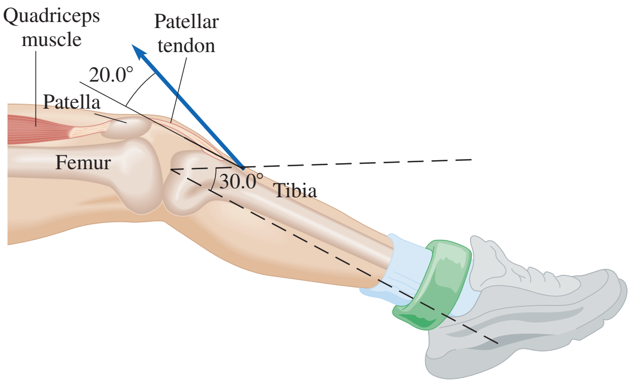
112. ✦ A roller coaster is towed up an incline at a steady speed of 0.50 m/s by a chain parallel to the surface of the incline. The slope is 3.0%, which means that the elevation increases by 3.0 m for every 100.0 m of horizontal distance. The mass of the roller coaster is 400.0 kg. Ignoring friction, what is the magnitude of the force exerted on the roller coaster by the chain?

113. An airplane is cruising along in a horizontal level flight at a constant velocity, heading due west. (a) If the weight of the plane is $2.6 \times 10^4$ N, what is the net force on the plane? (b) With what force does the air push upward on the plane?

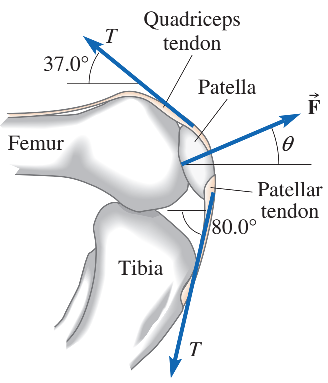
114. A young boy with a broken leg is undergoing traction. (a) Find the magnitude of the total force of the traction apparatus applied to the leg, assuming the weight of the leg is 22 N and the weight hanging from the traction apparatus is also 22 N. (b) What is the horizontal component of the traction force acting on the leg? (c) What is the magnitude of the force exerted on the femur by the lower leg?




115. A person is doing leg lifts with 3.00-kg ankle weights. The lower leg itself has a mass of 5.00 kg. When the leg is held still at an angle of 30.0° with respect to the horizontal, the patellar tendon pulls on the tibia with a force of 337 N at an angle of 20.0° *with respect to the lower leg*. Find the magnitude and direction of the force exerted on the tibia by the femur.




116. The figure shows the quadriceps and the patellar tendons attached to the patella (the kneecap). If the tension $T$ in each tendon is 1.30 kN, what is (a) the magnitude and (b) the direction of the contact force $\vec{\mathbf{F}}$ exerted on the patella by the femur?

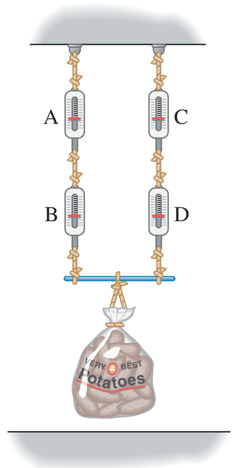



117. ✦ Ⓒ A toy freight train consists of an engine and three identical cars. The train is moving to the right at constant speed along a straight, level track. Three spring scales are used to connect the cars as follows: spring scale A is located between the engine and the first car; scale B is between the first and second cars; scale C is between the second and third cars. (a) If air resistance and friction are negligible, what are the relative readings on the three spring scales A, B, and C? (b) Repeat part (a), taking air resistance and friction into consideration this time. [*Hint:* Draw an FBD for the car in the middle.] (c) If air resistance and friction together cause a force of magnitude 5.5 N on each car, directed toward the left, find the readings of scales A, B, and C.

118. The coefficient of static friction between a block and a horizontal floor is 0.40, while the coefficient of kinetic friction is 0.15. The mass of the block is 5.0 kg. A horizontal force is applied to the block and slowly increased. (a) What is the value of the applied horizontal force at the instant that the block starts to slide? (b) What is the net force on the block after it starts to slide?

119. ✦ A box full of books rests on a wooden floor. The normal force the floor exerts on the box is 250 N. (a) You push horizontally on the box with a force of 120 N, but it refuses to budge. What can you say about the coefficient of static friction between the box and the floor? (b) If you must push horizontally on the box with a force of at least 150 N to start it sliding, what is the coefficient of static friction? (c) Once the box is sliding, you only have to push with a force of 120 N to keep it sliding. What is the coefficient of kinetic friction?

120. ✦ Four *identical* spring scales, A, B, C, and D are used to hang a 220.0-N sack of potatoes. (a) Assume that the scales have negligible weights and that all four scales show the same reading. What is the reading of each scale? (b) Suppose that each scale has a weight of 5.0 N. If scales B and D show the same reading, what is the reading of each scale?



121. In the sport of curling, a player slides a 20.0-kg granite stone down a 38-m-long ice rink. Draw FBDs for the stone (a) while it sits at rest on the ice; (b) while it slides down the rink; (c) during a head-on collision with an opponent's stone that was at rest on the ice.


122. ✦ A refrigerator magnet weighing 0.14 N is used to hold up a photograph weighing 0.030 N. The magnet attracts the refrigerator door with a magnetic force of 2.10 N. (a) Identify the interactions between the magnet and other objects. (b) Draw an FBD for the magnet, showing all the forces that act on it. (c) Which of these forces are long-range and which are contact forces? (d) Find the magnitudes of all the forces acting on the magnet.

123. A computer weighing 87 N rests on the horizontal surface of your desk. The coefficient of friction between the computer and the desk is 0.60. (a) Draw an FBD for the computer. (b) What is the magnitude of the frictional force acting on the computer? (c) How hard would you have to push on it to get it to start to slide across the desk?

124. ✦ A 50.0-kg crate is suspended between the floor and the ceiling using two spring scales, one attached to the ceiling and one to the floor. If the lower scale reads 120 N, what is the reading of the upper scale? Ignore the weight of the scales.

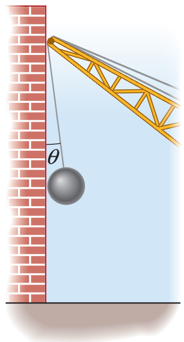
125. ✦ Spring scale A is attached to the ceiling. A 10.0-kg mass is suspended from the scale. A second spring scale, B, is hanging from a hook at the bottom of the 10.0-kg mass and a 4.0-kg mass hangs from the second spring scale. (a) What are the readings of the two scales if the masses of the scales are negligible? (b) What are the readings if each scale has a mass of 1.0 kg?

126. The tallest spot on Earth is Mt. Everest, which is 8850 m above sea level. If the radius of the Earth to sea level is 6370 km, how much does the gravitational field strength change between the sea level value at that location (9.826 N/kg) and the top of Mt. Everest?

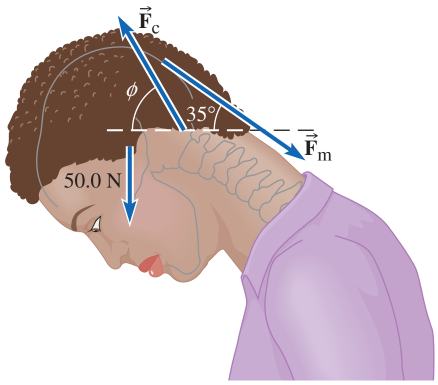
127. By what percentage does the weight of an object change when it is moved from the equator at sea level, where the effective value of $g$ is 9.784 N/kg, to the North Pole where $g = 9.832$ N/kg?

128. Two canal workers pull a barge along the narrow waterway at a constant speed. One worker pulls with a force of 105 N at an angle of 28° with respect to the forward motion of the barge, and the other worker, on the opposite tow path, pulls at an angle of 38° relative to the barge motion. Both ropes are parallel to the ground. (a) With what magnitude force should the second worker pull to make the sum of the two forces be in the forward direction? (b) What is the magnitude of the force on the barge from the two tow ropes?

129. A large wrecking ball of mass $m$ is resting against a wall. It hangs from the end of a cable that is attached at its upper end to a crane that is just touching the wall. The cable makes an angle of $\theta$ with the wall. Ignoring friction between the ball and the wall, find the tension in the cable.




130. ✦ A student's head is bent over her physics book. The head weighs 50.0 N and is supported by the muscle force $\vec{\mathbf{F}}_m$ exerted by the neck extensor muscles and by the contact force $\vec{\mathbf{F}}_c$ exerted at the atlantooccipital joint. Given that the magnitude of $\vec{\mathbf{F}}_m$ is 60.0 N and is directed 35° below the horizontal, find (a) the magnitude and (b) the direction of $\vec{\mathbf{F}}_c$.




131. ✦ The mass of the Moon is 0.0123 times that of the Earth. A spaceship is traveling along a line connecting the centers of the Earth and the Moon. At what

distance from the Earth does the spaceship find the gravitational pull of the Earth equal in magnitude to that of the Moon? Express your answer as a percentage of the distance between the centers of the two bodies.

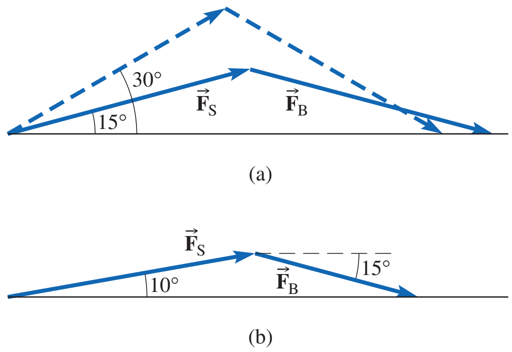
132. A 320-kg satellite is in orbit around the Earth 16 000 km above the Earth's surface. (a) What is the weight of the satellite when in orbit? (b) What was its weight when it was on the Earth's surface, before being launched? (c) While it orbits the Earth, what force does the satellite exert on the Earth?

133. ✦ (a) If a spacecraft moves in a straight line between the Earth and the Sun, at what point would the force of gravity on the spacecraft due to the Sun be as large as that due to the Earth? (b) If the spacecraft is close to, but not at, this equilibrium point, does the net force on the spacecraft tend to push it toward or away from the equilibrium point? [*Hint:* Imagine the spacecraft a small distance *d* closer to the Earth and find out which gravitational force is stronger.]

## Answers to Practice Problems

**2.1** No, the checkbook balance may increase or decrease, but there is no spatial direction associated with it. When we say it "goes down," we do not mean that it moves in a direction toward the center of the Earth! Rather, we really mean that it decreases. The balance is a scalar.

**2.2** Answer: (a) smaller (b) yes; $F_S > F_B$.

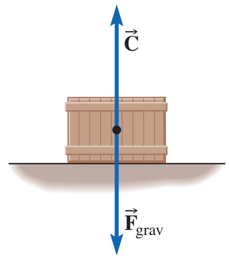



**2.3** 157 N, 57° below the +*x*-axis

**2.4** (a) $F_x$ = 49.1 N, $F_y$ = 2.9 N; (b) *F* = 49.2 N; (c) 3.4° above the horizontal

**2.5** In the first case, the principle of inertia says that Emma tends to stay at rest with respect to the ground as the subway car begins to move forward, until forces acting on her (exerted by the strap and the floor) make her move forward. In the second case, Emma keeps moving forward with respect to the ground with constant speed as the subway car slows down, until forces acting on her make her slow down as well.

**2.6** 80 N upward




**2.7** 0.5 kN downward

**2.8** 760 N, 81.7° above the −*x*-axis or 8.3° to the left of the +*y*-axis

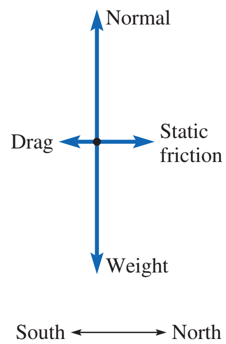
**2.9** The contact force exerted on the floor by the chest. 870 N, 59° below the rightward horizontal (+*x*-axis).

**2.10** For $m_1 = m_2$ = 1000 kg and *r* = 4 m, $F \approx 4$ µN, which is about the same magnitude as the weight of a mosquito. The claim that this tiny force caused the collision is ridiculous.

**2.11** 0.57 N or 0.13 lb

**2.12** The chest is in equilibrium, so the net force on it is zero. Setting the net force equal to zero separately for the horizontal and vertical components gives the answer: the normal force is 750 N, up, and the frictional force is 110 N, to the left. The quantity $\mu_s N$ is the *maximum* possible magnitude of the force of static friction for a surface. In this problem, the frictional force does not necessarily have the maximum possible magnitude.

**2.13** (a)

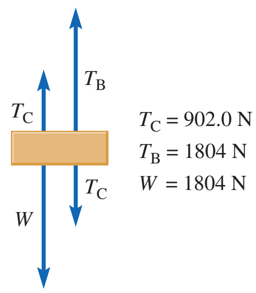



(b) Weight of the car = 11.0 kN; (c) 2.1 kN northward

**2.14** (a) 110 N; (b) 230 N

**2.15** 3100 N

**2.16**

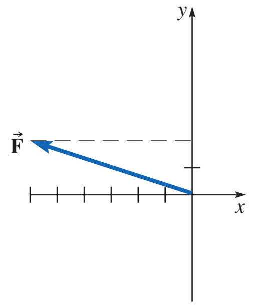


## Answers to Checkpoints

**2.1** Contact force exerted on the player by the ball; contact force exerted on the player by the ground; contact force exerted on the player by the air; gravitational force exerted on the player by Earth.

**2.2** 30 N south

**2.3**




**2.4** No, the net force is the sum of *all* the forces acting on the pulley. The patient's foot also exerts a force on the pulley.

**2.5** The two forces exerted by the two children on the toy cannot be interaction partners because they act on the *same* object (the toy), not on two different objects. Interaction partners act on different objects, one on each of the two objects that are interacting. The interaction partner of the force exerted by one child on the toy is the force that the toy exerts on that child.

**2.6** The weight of the gear decreases as the value of $g$ decreases. The mass of the gear does not change.

**2.7** One upward normal force on each leg due to the floor and one downward normal force on the desktop due to the laptop.