Everyday Forces

SECTION 4

SECTION OBJECTIVES

- **Explain the difference between mass and weight.**
- **Find the direction and magnitude of normal forces.**
- **Describe air resistance as a form of friction.**
- **Use coefficients of friction to calculate frictional force.**

WEIGHT

How do you know that a bowling ball weighs more than a tennis ball? If you imagine holding one ball in each hand, you can imagine the downward forces acting on your hands. Because the bowling ball has more mass than the tennis ball does, gravitational force pulls more strongly on the bowling ball. Thus, the bowling ball pushes your hand down with more force than the tennis ball does.

The gravitational force exerted on the ball by Earth, $\mathbf{F_g}$, is a vector quantity, directed toward the center of Earth. The magnitude of this force, F_g, is a scalar quantity called **weight.** The weight of an object can be calculated using the equation $F_g = ma_g$, where a_g is the magnitude of the acceleration due to gravity, or free-fall acceleration. On the surface of Earth, $a_g = g$, and $F_g = mg$. In this book, $g = 9.81\ \text{m/s}^2$ unless otherwise specified.

weight

a measure of the gravitational force exerted on an object; its value can change with the location of the object in the universe

Weight, unlike mass, is not an inherent property of an object. Because it is equal to the magnitude of the force due to gravity, weight depends on location. For example, if the astronaut in **Figure 10** weighs 800 N (180 lb) on Earth, he would weigh only about 130 N (30 lb) on the moon. As you will see in the chapter "Circular Motion and Gravitation," the value of a_g on the surface of a planet depends on the planet's mass and radius. On the moon, a_g is about $1.6\ \text{m/s}^2$—much smaller than $9.81\ \text{m/s}^2$.

Even on Earth, an object's weight may vary with location. Objects weigh less at higher altitudes than they do at sea level because the value of a_g decreases as distance from the surface of Earth increases. The value of a_g also varies slightly with changes in latitude.

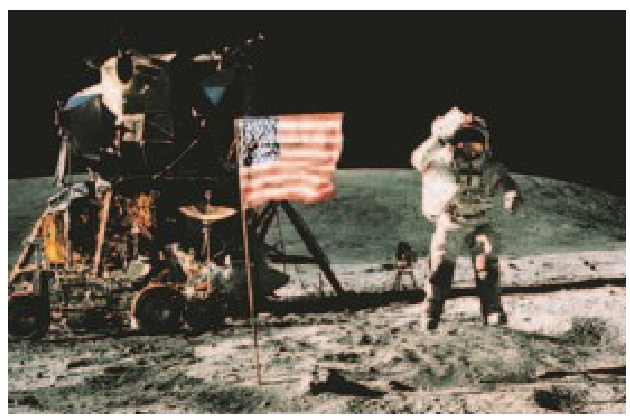

Figure 10
On the moon, astronauts weigh much less than they do on Earth.

THE NORMAL FORCE

Imagine a television set at rest on a table. We know that the gravitational force is acting on the television. How can we use Newton's laws to explain why the television does not continue to fall toward the center of Earth?

An analysis of the forces acting on the television will reveal the forces that are in equilibrium. First, we know that the gravitational force of Earth, $\mathbf{F_g}$, is acting downward. Because the television is in equilibrium, we know that another force, equal in magnitude to $\mathbf{F_g}$ but in the opposite direction, must be acting on it. This force is the force exerted on the television by the table. This force is called the **normal force,** $\mathbf{F_n}$.

normal force

a force that acts on a surface in a direction perpendicular to the surface

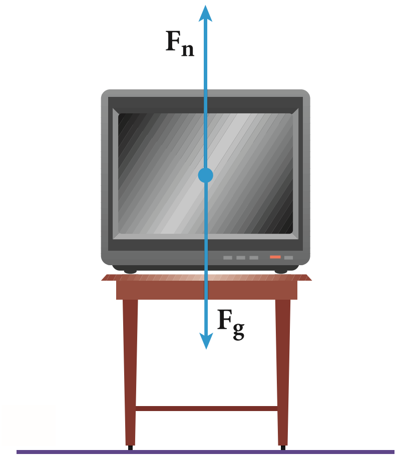

Figure 11
In this example, the normal force, $\mathbf{F_n}$, is equal and opposite to the force due to gravity, $\mathbf{F_g}$.

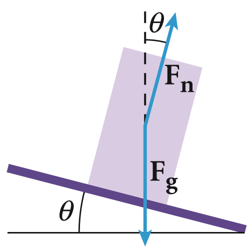

Figure 12
The normal force is not always opposite the force due to gravity, as shown by this example of a refrigerator on a loading ramp.

The word *normal* is used because the direction of the contact force is perpendicular to the table surface and one meaning of the word *normal* is "perpendicular." **Figure 11** shows the forces acting on the television.

The normal force is always perpendicular to the contact surface but is not always opposite in direction to the force due to gravity. **Figure 12** shows a free-body diagram of a refrigerator on a loading ramp. The normal force is perpendicular to the ramp, not directly opposite the force due to gravity. In the absence of other forces, the normal force, $\mathbf{F_n}$, is equal and opposite to the component of $\mathbf{F_g}$ that is perpendicular to the contact surface. The magnitude of the normal force can be calculated as $F_n = mg \cos \theta$. The angle θ is the angle between the normal force and a vertical line and is also the angle between the contact surface and a horizontal line.

THE FORCE OF FRICTION

Consider a jug of juice at rest (in equilibrium) on a table, as in **Figure 13(a).** We know from Newton's first law that the net force acting on the jug is zero. Newton's second law tells us that any additional unbalanced force applied to the jug will cause the jug to accelerate and to remain in motion unless acted on by another force. But experience tells us that the jug will not move at all if we apply a very small horizontal force. Even when we apply a force large enough to move the jug, the jug will stop moving almost as soon as we remove this applied force.

Friction opposes the applied force

When the jug is at rest, the only forces acting on it are the force due to gravity and the normal force exerted by the table. These forces are equal and opposite, so the jug is in equilibrium. When you push the jug with a small horizontal force **F**, as shown in **Figure 13(b),** the table exerts an equal force in the opposite direction. As a result, the jug remains in equilibrium and therefore also remains at rest. The resistive force that keeps the jug from moving is called the force of **static friction,** abbreviated as $\mathbf{F_s}$.

static friction

the force that resists the initiation of sliding motion between two surfaces that are in contact and at rest

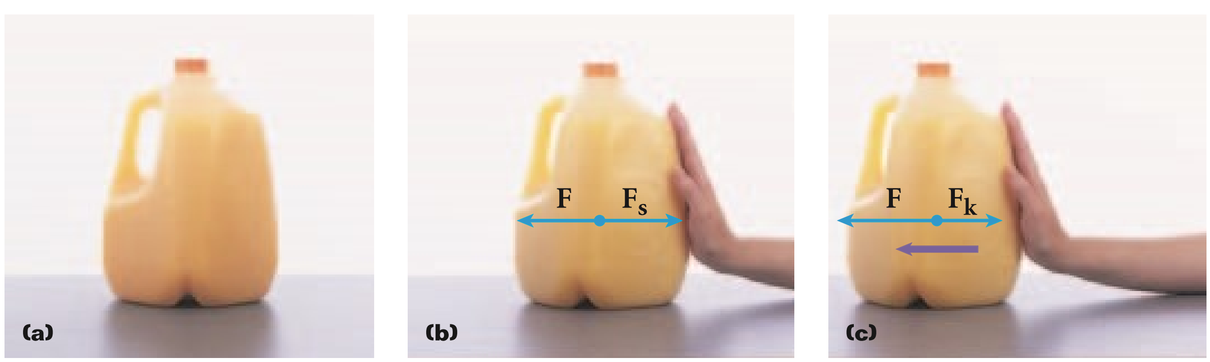

Figure 13 **(a)** Because this jug of juice is in equilibrium, any unbalanced horizontal force applied to it will cause the jug to accelerate. **(b)** When a small force is applied, the jug remains in equilibrium because the static-friction force is equal but opposite to the applied force. **(c)** The jug begins to accelerate as soon as the applied force exceeds the opposing static-friction force.

As long as the jug does not move, the force of static friction is always equal to and opposite in direction to the component of the applied force that is parallel to the surface ($F_s = -F_{applied}$). As the applied force increases, the force of static friction also increases; if the applied force decreases, the force of static friction also decreases. When the applied force is as great as it can be without causing the jug to move, the force of static friction reaches its maximum value, $\mathbf{F_{s,max}}$.

Kinetic friction is less than static friction

When the applied force on the jug exceeds $\mathbf{F_{s,max}}$, the jug begins to move with an acceleration to the left, as shown in **Figure 13(c).** A frictional force is still acting on the jug as the jug moves, but that force is actually less than $\mathbf{F_{s,max}}$. The retarding frictional force on an object in motion is called the force of **kinetic friction** **($\mathbf{F_k}$).** The magnitude of the net force acting on the object is equal to the difference between the applied force and the force of kinetic friction ($F_{applied} - F_k$).

kinetic friction

the force that opposes the movement of two surfaces that are in contact and are sliding over each other

At the microscopic level, frictional forces arise from complex interactions between contacting surfaces. Most surfaces, even those that seem very smooth to the touch, are actually quite rough at the microscopic level, as illustrated in **Figure 14.** Notice that the surfaces are in contact at only a few points. When two surfaces are stationary with respect to each other, the surfaces stick together somewhat at the contact points. This *adhesion* is caused by electrostatic forces between molecules of the two surfaces.

TIP *In free-body diagrams, the force of friction is always parallel to the surface of contact. The force of kinetic friction is always opposite the direction of motion. To determine the direction of the force of static friction, use the principle of equilibrium. For an object in equilibrium, the frictional force must point in the direction that results in a net force of zero.*

The force of friction is proportional to the normal force

It is easier to push a chair across the floor at a constant speed than to push a heavy desk across the floor at the same speed. Experimental observations show that the magnitude of the force of friction is approximately proportional to the magnitude of the normal force that a surface exerts on an object. Because the desk is heavier than the chair, the desk also experiences a greater normal force and therefore greater friction.

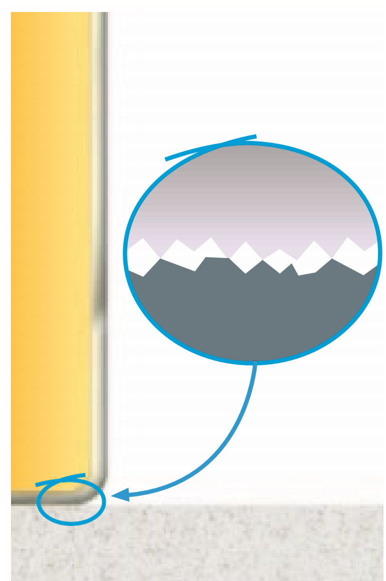

Figure 14
On the microscopic level, even very smooth surfaces make contact at only a few points.

Friction can be calculated approximately

Keep in mind that the force of friction is really a macroscopic effect caused by a complex combination of forces at a microscopic level. However, we can approximately calculate the force of friction with certain assumptions. The relationship between normal force and the force of friction is one factor that affects friction. For instance, it is easier to slide a light textbook across a desk than it is to slide a heavier textbook. The relationship between the normal force and the force of friction provides a good approximation for the friction between dry, flat surfaces that are at rest or sliding past one another.

The force of friction also depends on the composition and qualities of the surfaces in contact. For example, it is easier to push a desk across a tile floor than across a floor covered with carpet. Although the normal force on the desk is the same in both cases, the force of friction between the desk and the carpet is higher than the force of friction between the desk and the tile. The quantity that expresses the dependence of frictional forces on the particular surfaces in contact is called the **coefficient of friction.** The coefficient of friction between a waxed snowboard and the snow will affect the acceleration of the snowboarder shown in **Figure 15.** The coefficient of friction is represented by the symbol μ, the lowercase Greek letter *mu.*

coefficient of friction

the ratio of the magnitude of the force of friction between two objects in contact to the magnitude of the normal force with which the objects press against each other

The coefficient of friction is a ratio of forces

The coefficient of friction is defined as the ratio of the force of friction to the normal force between two surfaces. The *coefficient of kinetic friction* is the ratio of the force of kinetic friction to the normal force.

$$\mu_k = \frac{F_k}{F_n}$$

The *coefficient of static friction* is the ratio of the maximum value of the force of static friction to the normal force.

$$\mu_s = \frac{F_{s,max}}{F_n}$$

If the value of μ and the normal force on the object are known, then the magnitude of the force of friction can be calculated directly.

$$F_f = \mu F_n$$

Table 2 shows some experimental values of μ_s and μ_k for different materials. Because kinetic friction is less than or equal to the maximum static friction, the coefficient of kinetic friction is always less than or equal to the coefficient of static friction.

Figure 15
Snowboarders wax their boards to minimize the coefficient of friction between the boards and the snow.

Table 2 Coefficients of Friction (Approximate Values)

	μ_s	μ_k		μ_s	μ_k
steel on steel	0.74	0.57	waxed wood on wet snow	0.14	0.1
aluminum on steel	0.61	0.47	waxed wood on dry snow	—	0.04
rubber on dry concrete	1.0	0.8	metal on metal (lubricated)	0.15	0.06
rubber on wet concrete	—	0.5	ice on ice	0.1	0.03
wood on wood	0.4	0.2	Teflon on Teflon	0.04	0.04
glass on glass	0.9	0.4	synovial joints in humans	0.01	0.003

SAMPLE PROBLEM D

Coefficients of Friction

PROBLEM

A 24 kg crate initially at rest on a horizontal floor requires a 75 N horizontal force to set it in motion. Find the coefficient of static friction between the crate and the floor.

SOLUTION

Given: $F_{s,max} = F_{applied} = 75 \text{ N} \quad m = 24 \text{ kg}$

Unknown: $\mu_s = ?$

Use the equation for the coefficient of static friction.

$$\mu_s = \frac{F_{s,max}}{F_n} = \frac{F_{s,max}}{mg}$$

$$\mu_s = \frac{75 \text{ N}}{24 \text{ kg} \times 9.81 \text{ m/s}^2}$$

$$\boxed{\mu_s = 0.32}$$

TIP *Because the crate is on a horizontal surface, the magnitude of the normal force (F_n) equals the crate's weight (mg).*

PRACTICE D

Coefficients of Friction

1. Once the crate in Sample Problem D is in motion, a horizontal force of 53 N keeps the crate moving with a constant velocity. Find μ_k, the coefficient of kinetic friction, between the crate and the floor.

2. A 25 kg chair initially at rest on a horizontal floor requires a 165 N horizontal force to set it in motion. Once the chair is in motion, a 127 N horizontal force keeps it moving at a constant velocity.

a. Find the coefficient of static friction between the chair and the floor.
b. Find the coefficient of kinetic friction between the chair and the floor.

3. A museum curator moves artifacts into place on various different display surfaces. Use the values in **Table 2** to find $F_{s,max}$ and F_k for the following situations:

a. moving a 145 kg aluminum sculpture across a horizontal steel platform
b. pulling a 15 kg steel sword across a horizontal steel shield
c. pushing a 250 kg wood bed on a horizontal wood floor
d. sliding a 0.55 kg glass amulet on a horizontal glass display case