4-3
Newton's second and third laws

4-3 SECTION OBJECTIVES

- **Describe the acceleration of an object in terms of its mass and the net external force acting on it.**
- **Predict the direction and magnitude of the acceleration caused by a known net external force.**
- **Identify action-reaction pairs.**
- **Explain why action-reaction pairs do not result in equilibrium.**

NEWTON'S SECOND LAW

From Newton's first law, we know that an object with no net external force acting on it is in a state of equilibrium. We also know that an object experiencing a net external force undergoes a change in its velocity. But exactly how much does a known force affect the motion of an object?

Force is proportional to mass and acceleration

Imagine pushing a stalled car through a level intersection, as shown in **Figure 4-16.** Because a net force causes an object to accelerate, the speed of the car will increase. When you push the car by yourself, however, the acceleration will be so small that it will take a long time for you to notice an increase in the car's speed. If you get several friends to help you, the net force on the car is much greater, and the car will soon be moving so fast that you will have to run to keep up with it. This happens because the acceleration of an object is directly proportional to the net external force acting on it.

Experience pushing objects reveals that the mass of an object also affects its acceleration. If you push a bowling ball and a tennis ball with the same force, the tennis ball will accelerate quickly, while the bowling ball will accelerate slowly. Similarly, a lightweight car accelerates faster than a heavy truck if the same force is applied to both. It requires much less force to accelerate a low-mass object than it does to accelerate a high-mass object at the same rate. This is because an object with smaller mass has less inertia, or tendency to maintain its state of motion, than an object with greater mass.

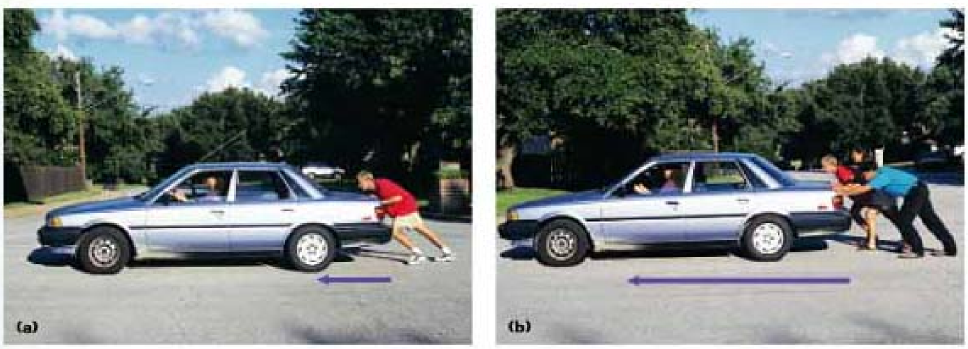

Figure 4-16
(a) A small force on an object causes a small acceleration, but **(b)** a larger force causes a larger acceleration.

Newton's second law relates force, mass, and acceleration

The relationships between mass, force, and acceleration are quantified in **Newton's second law.**

> **NEWTON'S SECOND LAW**
>
> **The acceleration of an object is directly proportional to the net external force acting on the object and inversely proportional to the object's mass.**

According to Newton's second law, if equal forces are applied to two objects of different masses, the object with greater mass will experience a smaller acceleration, and the object with less mass will experience a greater acceleration.

In equation form, we can state Newton's law as

$$\Sigma \mathbf{F} = m\mathbf{a}$$

net external force = mass × acceleration

where **a** is the acceleration of the object, *m* is its mass, and **ΣF** represents the *vector sum of all external forces acting on the object.* This relationship makes it possible, when the mass of the object is known, to determine what effect a given force will have on an object's motion.

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> **"Force and Inertia"**
> provides an interactive lesson with guided problem-solving practice to teach you about forces and Newton's laws.

SAMPLE PROBLEM 4B

Newton's second law

PROBLEM

Roberto and Laura are studying across from each other at a wide table. Laura slides a 2.2 kg book toward Roberto. If the net external force acting on the book is 2.6 N to the right, what is the book's acceleration?

SOLUTION

Given: $m = 2.2$ kg

$\mathbf{F}_{net} = \Sigma \mathbf{F} = 2.6$ N, to the right

Unknown: $a = ?$

Use Newton's second law, and solve for a.

$$a = \frac{\Sigma \mathbf{F}}{m}$$

$$a = \frac{2.6 \text{ N}}{2.2 \text{ kg}}$$

$$\boxed{a = 1.2 \text{ m/s}^2 \text{ to the right}}$$

> **CALCULATOR SOLUTION**
>
> Your calculator will give you an answer of 1.1818 . . . for the acceleration. Because all values in the problem have only two significant digits, this value must be rounded up to 1.2.

PRACTICE 4B

Newton's second law

1. The net external force on the propeller of a 3.2 kg model airplane is 7.0 N forward. What is the acceleration of the airplane?
2. The net external force on a golf cart is 390 N north. If the cart has a total mass of 270 kg, what are the magnitude and direction of its acceleration?
3. A car has a mass of 1.50×10^3 kg. If the force acting on the car is 6.75×10^3 N to the east, what is the car's acceleration?
4. A 2.0 kg otter starts from rest at the top of a muddy incline 85 cm long and slides down to the bottom in 0.50 s. What net external force acts on the otter along the incline?
5. A soccer ball kicked with a force of 13.5 N accelerates at 6.5 m/s^2 to the right. What is the mass of the ball?

Conceptual Challenge

1. Gravity and rocks

The force of gravity is twice as great on a 2 kg rock as it is on a 1 kg rock. Why doesn't the 2 kg rock have a greater free-fall acceleration?

2. Leaking truck

A truck loaded with sand accelerates at 0.5 m/s^2 on the highway. If the driving force on the truck remains constant, what happens to the truck's acceleration if sand leaks at a constant rate from a hole in the truck bed?

In solving problems, it is often easier to break the equation for Newton's second law into components. The sum of forces acting in the x direction equals the mass times the acceleration in the x direction ($\Sigma F_x = ma_x$), and the sum of forces in the y direction equals the mass times the acceleration in the y direction ($\Sigma F_y = ma_y$). If the net external force is zero, then $\mathbf{a} = 0$, which corresponds to the equilibrium situation where $\mathbf{v}$ is either constant or zero.

NEWTON'S THIRD LAW

A force is exerted on an object when that object interacts with some other object in its environment. Consider a moving car colliding with a concrete barrier. The car exerts a force on the barrier at the moment of collision, just as you apply force to a door when you push it or to a ball when you kick it. Furthermore, the barrier exerts a force on the car so that the car rapidly slows down after coming into contact with the barrier.

Forces always exist in pairs

From examples like this, Newton recognized that a single isolated force cannot exist. Instead, *forces always exist in pairs.* The car exerts a force on the barrier, and at the same time, the barrier exerts a force on the car. Newton described this type of situation with his **third law of motion.**

NEWTON'S THIRD LAW

If two objects interact, the magnitude of the force exerted on object 1 by object 2 is equal to the magnitude of the force simultaneously exerted on object 2 by object 1, and these two forces are opposite in direction.

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An alternative statement of this law is that *for every action there is an equal and opposite reaction.* When two objects interact with one another, the forces they mutually exert on each other are called an **action-reaction pair.** The force that object 1 exerts on object 2 is sometimes called the *action force,* while the force that object 2 exerts on object 1 is called the *reaction force.* The action force is equal in magnitude and opposite in direction to the reaction force. The terms *action* and *reaction* sometimes cause confusion because they are used a little differently in physics than they are in everyday speech. In everyday speech, the word *reaction* is used to refer to something that happens *after* and *in response to* an event. In physics, however, the reaction force occurs at exactly the same time as the action force.

action-reaction pair

a pair of simultaneous equal but opposite forces resulting from the interaction of two objects

Because the forces coexist, either force can be called the action or the reaction. For example, you could call the force the car exerts on the barrier the action and the force the barrier exerts on the car the reaction. Likewise, you could choose to call the force the barrier exerts on the car the action and to call the force the car exerts on the barrier the reaction.

Action and reaction forces each act on different objects

The most important thing to remember about action-reaction pairs is that each force acts on a different object. Consider the task of driving a nail into a block of wood, as illustrated in **Figure 4-17.** To accelerate the nail and drive it into the block, the hammer exerts a force on the nail. According to Newton's third law, the nail exerts a force on the hammer that is equal to the magnitude of the force the hammer exerts on the nail.

Figure 4-17
The nail exerts a force on the hammer that is equal and opposite to the force the hammer exerts on the nail.

The concept of action-reaction pairs is a common source of confusion because some people assume incorrectly that the equal and opposite forces balance one another and make any change in the state of motion impossible. If the nail exerts a force on the hammer that is equal to the force the hammer exerts on the nail, why doesn't the nail remain at rest?

Because they act on different objects, action-reaction pairs do not result in equilibrium. The motion of the nail is affected only by the forces acting on the nail. The force the nail exerts on the hammer affects only the hammer, not the nail. To determine whether the nail will accelerate, draw a free-body diagram to isolate the forces acting on the nail alone, as shown in **Figure 4-18.** The force of the nail on the hammer is not included in the diagram because it does not affect the motion of the nail. According to the diagram, the nail will be driven into the wood because there is a net external force acting on the nail.

Figure 4-18
The net external force acting on the nail drives it to the left into the wood.

Field forces also exist in pairs

Newton's third law also applies to field forces. For example, consider the gravitational force exerted by Earth on an object. During calibration at the crash-test site, engineers calibrate the sensors in the heads of crash-test dummies by removing the heads and dropping them from a known height.

CONCEPT PREVIEW

Gravitational force is covered in Chapter 7, Section 7-3.

The force Earth exerts on a dummy's head is $\mathbf{F_g}$. Let's call this force the action. What is the reaction? Because $\mathbf{F_g}$ is the force exerted on the falling head by Earth, the reaction to $\mathbf{F_g}$ is the force exerted on Earth by the falling head.

According to Newton's third law, the force of the dummy on Earth is equal to the force of Earth on the dummy. Thus, as a falling object accelerates toward Earth, Earth also accelerates toward the object.

The thought that Earth accelerates toward the dummy's head may seem to contradict our experience. One way to make sense of this is to refer to Newton's second law. The mass of Earth is much greater than that of the dummy's head. Therefore, while the dummy's head undergoes a large acceleration due to the force of Earth, the acceleration of Earth due to this reaction force is negligibly small because of its enormous mass.

Section Review

1. A 6.0 kg object undergoes an acceleration of 2.0 m/s^2.
- **a.** What is the magnitude of the net external force acting on it?
- **b.** If this same force is applied to a 4.0 kg object, what acceleration is produced?

2. A child pulls a wagon with a horizontal force, causing it to accelerate. Newton's third law says that the wagon exerts an equal and opposite force on the child. How can the wagon accelerate? (*Hint:* Draw a free-body diagram for each object to help you answer this question.)

3. Identify the action-reaction pairs in the following situations:
- **a.** a person takes a step
- **b.** a snowball hits someone in the back
- **c.** a baseball player catches a ball
- **d.** a gust of wind strikes a window

4. The forces acting on a sailboat are 390 N north and 180 N east. If the boat (including crew) has a mass of 270 kg, what are the magnitude and direction of its acceleration?

5. **Physics in Action** If a small sports car collides head-on with a massive truck, which vehicle experiences the greater impact force? Which vehicle experiences the greater acceleration? Explain.