SECTION 3

Newton’s Second and Third Laws

SECTION OBJECTIVES

- Describe an object’s acceleration in terms of its mass and the net force acting on it.
- Predict the direction and magnitude of the acceleration caused by a known net force.
- Identify action-reaction pairs.

NEWTON’S SECOND LAW

From Newton’s first law, we know that an object with no net force acting on it is in a state of equilibrium. We also know that an object experiencing a net 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 7.** 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 change happens because the acceleration of an object is directly proportional to the net force acting on the object. (Note that this is an idealized example that disregards any friction forces that would hinder the motion. In reality, the car accelerates when the push is greater than the frictional force. However, when the force exerted by the pushers equals the frictional force, the net force becomes zero, and the car moves at a constant velocity.)

Experience reveals that the mass of an object also affects the object’s acceleration. A lightweight car accelerates more than a heavy truck if the same force is applied to both. Thus, it requires less force to accelerate a low-mass object than it does to accelerate a high-mass object at the same rate.

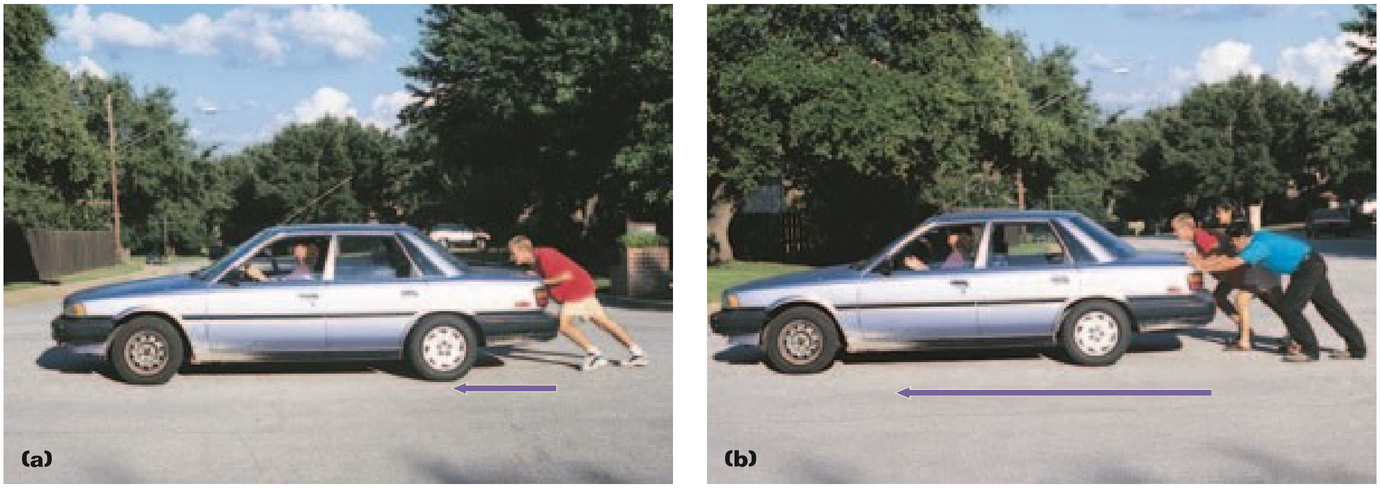

Figure 7
(a) A small force on an object causes a small acceleration, but **(b)** a larger force causes a larger acceleration.

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 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 follows:

NEWTON’S SECOND LAW

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

net force = mass × acceleration

In this equation, **a** is the acceleration of the object and *m* is the object’s mass. Note that Σ is the Greek capital letter *sigma,* which represents the sum of the quantities that come after it. In this case, **ΣF** represents the *vector sum of all external forces acting on the object,* or the net force.

SAMPLE PROBLEM C

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 force acting on the book is 1.6 N to the right, what is the book’s acceleration?

SOLUTION

Given: $m = 2.2$ kg

$\mathbf{F}_{net} = \Sigma \mathbf{F} = 1.6$ N to the right

Unknown: $\mathbf{a} = ?$

Use Newton’s second law, and solve for **a.**

$$\Sigma \mathbf{F} = m\mathbf{a}, \text{ so } \mathbf{a} = \frac{\Sigma \mathbf{F}}{m}$$

$$a = \frac{1.6 \text{ N}}{2.2 \text{ kg}} = 0.73 \text{ m/s}^2$$

$$\boxed{\mathbf{a} = 0.73 \text{ m/s}^2 \text{ to the right}}$$

TIP *If more than one force is acting on an object, you must find the net force as shown in Sample Problem B before applying Newton’s second law. The acceleration will be in the direction of the net force.*

PRACTICE C

Newton's Second Law

1. The net 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 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 the cart's 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 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?
5. 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 force acts on the otter along the incline?

TIP *For some problems, it may be easier to use the equation for Newton's second law twice: once for all of the forces acting in the x direction ($\Sigma F_x = ma_x$) and once for all of the forces acting in the y direction ($\Sigma F_y = ma_y$). If the net force in both directions is zero, then* $\mathbf{a} = 0$*, which corresponds to the equilibrium situation in which* **v** *is either constant or zero.*

Why it Matters

Conceptual Challenge

1. Gravity and Rocks

The force due to 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?

NEWTON'S THIRD LAW

A force is exerted on an object when that object interacts with another 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. Furthermore, the barrier exerts a force on the car so that the car rapidly slows down after coming into contact with the barrier. Similarly, when your hand applies a force to a door to push it open, the door simultaneously exerts a force back on your hand.

Forces always exist in pairs

From examples like those discussed in the previous paragraph, 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 that the objects 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.

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

Action and reaction forces each act on different objects

One 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 wood, as illustrated in **Figure 8.** To accelerate the nail and drive it into the wood, 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 that the hammer exerts on the nail.

Figure 8
The force that the nail exerts on the hammer is equal and opposite to the force that 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 force that the nail exerts on the hammer is equal to the force the hammer exerts on the nail, why doesn't the nail remain at rest?

The motion of the nail is affected only by the forces acting on the nail. To determine whether the nail will accelerate, draw a free-body diagram to isolate the forces acting on the nail, as shown in **Figure 9.** The force of the nail on the hammer is not included in the diagram because it does not act on the nail. According to the diagram, the nail will be driven into the wood because there is a net force acting on the nail. Thus, action-reaction pairs do not imply that the net force on either object is zero. The action-reaction forces are equal and opposite, but either object may still have a net force acting on it.

Figure 9
The net force acting on the nail drives the nail 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.

The force that 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 idea 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 Earth's enormous mass.

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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 force acting on the object?
- **b.** If this same force is applied to a 4.0 kg object, what acceleration is produced?

2. A child causes a wagon to accelerate by pulling it with a horizontal force. 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.)

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 the boat's acceleration?

5. **Critical Thinking** 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 your answers.