6.3 Newton's Third Law and Momentum

Newton's first and second laws apply to the motion of an *individual* object. Newton's third law applies to forces between interacting objects. Think about throwing a basketball (Figure 6.10). You feel the ball push back against your hand as you throw it. You apply a force to the ball to make it move. Where does the force against your hand come from? Can you predict your hand's motion and the basketball's motion after the throw?

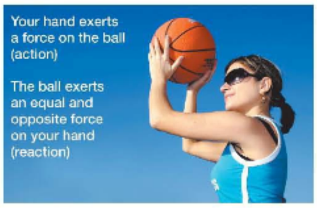
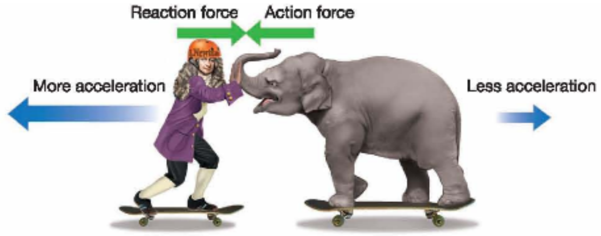


Figure 6.10: *You experience Newton's third law (action–reaction) whenever you apply force to any object, such as a basketball.*

Forces always come in matched pairs

An imaginary skateboard contest Imagine a skateboard contest between Isaac Newton and an elephant. They can push against each other, but not against the ground. The one whose skateboard moves the fastest wins. The elephant is much stronger and pushes off Newton with a huge force thinking he will surely win. But will he?



The winner Newton flies away with a great speed and the puzzled elephant moves backward with a much smaller speed. Newton wins—and will always win this contest against the elephant. No matter how hard the elephant pushes, Newton will always move away faster. Why?

Forces always come in pairs It takes force to make both Newton and the elephant move. Newton wins because *forces always come in pairs*. The elephant pushes against Newton and that *action* force pushes Newton away. The elephant's force against Newton creates a *reaction* force against the elephant. The action and reaction forces are equal in strength. Newton has much less mass so he has much more acceleration, therefore his speed is always greater.

JOURNAL

Think of three examples of action–reaction pairs that you experienced before class today. Write each one down and identify the action and reaction forces. Also write down what object each force acted on. Hint: The action and reaction forces never act on the same object.

The third law: Action and reaction

The first and second laws The first two laws of motion apply to individual objects. The first law says an object will remain at rest or in motion at a constant velocity unless acted upon by a net force. The second law states that acceleration equals the force on an object divided by the mass of the object.

The third law The third law of motion deals with pairs of objects. This is because *all forces come in pairs*. **Newton's third law** states that every action force creates a reaction force that is equal in strength and opposite in direction.

Every action force creates a reaction force that is equal in strength and opposite in direction.

Force pairs There can never be a single force acting alone, without its action–reaction partner. Forces *only* come in action–reaction pairs. In the skateboard contest, the net force is the difference between the force created by the elephant in one direction and the force created by Newton in the opposite direction. The *action* of this force acts on Newton and moves Newton. The *reaction* of the same force acts on the elephant and moves the elephant. The combined strength of Newton and the elephant create two equal and opposite forces, an action and a reaction.

The labels *action* and *reaction* The words *action* and *reaction* are just labels. It does not matter which force is called action and which is called reaction. You simply choose one to call the action and then call the other one the reaction (Figure 6.11).

Why action and reaction forces do not cancel each other out Why don't action and reaction forces cancel each other out? The reason is *action and reaction forces act on different objects*. For example, think again about throwing a ball. When you throw a ball, you apply the action force to the ball, creating the ball's acceleration. The reaction is the ball pushing back against your hand. The action acts on the ball and the reaction acts on your hand. The forces do not cancel each other out because they act on different objects. You can only cancel out forces acting on the same object (Figure 6.12).

VOCABULARY

Newton's third law - a law of motion that states that for every action force there is a reaction force equal in strength and opposite in direction.

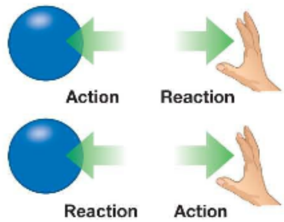


Figure 6.11: *It doesn't matter which force you call the action and which you call the reaction.*

Figure 6.12: *Action and reaction forces do not cancel each other out. One force acts on the ball, and the other force acts on the hand.*

Action and reaction forces

A skateboard example Think carefully about propelling a skateboard with your foot. Your foot presses backward against the ground (Figure 6.13). The force acts *on* the ground. However, *you* move, so a force must act on you, too. Why do you move? What force acts on you? You move because the action force of your foot against the ground creates a reaction force of the ground against your foot. You "feel" the ground because you sense the reaction force pressing on your foot. The reaction force is what makes you move because it acts on *you*.

Draw diagrams When sorting out action and reaction forces, it is helpful to draw diagrams. Draw each object apart from the other. Represent each force as an arrow in the appropriate direction. The illustration in Figure 6.13 is a good example of a diagram that shows a pair of action and reaction forces. The Solve It! box in the sidebar gives you an opportunity to think of your own example and draw a diagram.

Action and reaction guidelines Below are some guidelines to help you sort out action and reaction forces.

Guidelines for Action–Reaction Forces	Examples
Both forces are always there whenever any force occurs.	Your foot pushes (action) and the ground pushes back (reaction).
They always have the exact same strength.	The force arrows are the same length.
They always act in opposite directions.	The force arrows point in opposite directions.
They always act on different objects.	Your foot and the ground.
Both are real forces and can cause changes in motion.	You move forward on your skateboard.

Figure 6.13: *You move forward because of the reaction force of the ground on your foot.*

SOLVE IT!

Think of an action–reaction pair situation. Then, draw a diagram illustrating the action–reaction pair. Use the tips in the text for drawing your diagram.

Solving Problems: Action and Reaction

A woman with a weight of 600 newtons is sitting on a chair (Figure 6.14). Describe one action–reaction pair of forces in this situation.

1. Looking for: You are asked for a pair of action and reaction forces.

2. Given: You are given an action force—the woman's force on the chair. Her force is 600 N.

3. Relationships: Action–reaction forces are equal and opposite and act on different objects.

4. Solution: The downward force of 600 N exerted by the woman on the chair is an action. Therefore, the chair acting on the woman provides an upward force of 600 N and is a reaction.

Your turn...

a. A dog jumps up and sits on the lap of the woman who is sitting in the chair in Figure 6.14. The dog's weight is 40 newtons. What is the reaction force provided by the chair now?

b. A strong man now picks up the chair with the woman and the dog and holds them all above his head. If the upward force from the strong man is 700 newtons, what is the weight of the chair in newtons? Describe the different action–reaction pairs in this scenario.

c. A baseball player hits a ball with a bat. Describe an action–reaction pair of forces in this situation.

Figure 6.14: *An action is sitting on a chair.*

SOLVE FIRST LOOK LATER

a. 640 N

b. The weight of the chair is 60 N. Action–reaction pairs include the dog–woman's lap, the woman–chair, the chair–strongman, and the strongman–ground.

c. The force of the bat on the ball (action) accelerates the ball. The force of the ball on the bat (reaction) slows down the swinging bat.

Collisions and momentum

The effect of forces Newton's third law tells us that when two objects collide, they exert equal and opposite forces on each other. However, the *effect* of the force is not always the same. Imagine two hockey players moving at the same speed toward each other, one with twice the mass of the other. The force on each during the collision is the same strength, but they do not have the same change in motion during the collision.

Momentum When studying motion related to collisions, we can predict how two colliding objects might move using Newton's third law of motion and *momentum*. **Momentum** is the mass of a object times its velocity. The units for momentum are kilogram-meter per second (kg · m/s).

MOMENTUM

$$p = mv$$

Momentum (kg · m/s); Mass (kg); Velocity (m/s)

The law of conservation of momentum Using this information, we can determine the momentum of each player in the example above. The **law of conservation of momentum** states that as long as the interacting objects are not influenced by outside forces (like friction) the total amount of momentum is constant (does not change). This means that the total amount of momentum for the colliding hockey players before the collision equals the total amount of momentum afterward. Also, any momentum lost by one player is gained by the other one.

VOCABULARY

momentum - the mass of an object times its velocity.

law of conservation of momentum - a law that states that as long as interacting objects are not influenced by outside forces, the total amount of momentum is constant.

SOLVE IT!

Calculate: Use the momentum formula to find the momentum of each hockey player before they collide.

Player #1: m = 80 kg; v = 2 m/s

Player #2: m = 40 kg; v = 3 m/s

Predict: Let's say the motion of Player #1 is in the positive direction and the motion of Player #2 is in the negative direction. Based on your momentum calculations, in which direction do you think the two combined players will move after the collision?

Understanding the law of conservation of momentum

Positive and negative momentum The forces on any two interacting objects are always equal and opposite. Similarly, the momentum of two interacting objects is equal and opposite. Therefore, it makes sense to use positive and negative values to tell the direction of motion (Figure 6.15). Momentum can be positive (moving to the right) or negative (moving to the left) (Figure 6.15).

A ball example Let's say a skateboarder is standing on a skateboard and is holding a ball. Before he throws the ball, his velocity (and the ball's) is zero. Since momentum is mass times velocity, the total momentum is also zero. The law of conservation of momentum says that after the ball is thrown, the total momentum still has to be zero. Here's where positive and negative values help us.

Conservation of momentum If the ball has a mass of 1 kilogram and the skateboarder throws it at a velocity of –20 m/s to the left, the ball takes away –20 kg · m/s of momentum. To make the total momentum zero, the skateboarder must take away +20 kg · m/s of momentum. If his mass is 40 kilogram and you ignore friction, then his speed is +0.5 m/s to the right (Figure 6.16).

More mass results in less acceleration Because of his greater mass, the skateboarder will have a slower speed. The ball, which has less mass, has the greater speed. *They each have equal and opposite momentum after the throw.* The two objects, the skateboarder and the ball, have different speeds because they have different masses, *not because the forces are different!*

Jet planes and rockets Rockets and jet planes use the law of conservation of momentum to move. In a process called jet propulsion, a jet moves forward when the engine pushes exhaust air at very high speed out of the back of the engine. The momentum lost by the air going backward is compensated for by the momentum gained by the jet moving forward. Similarly, a rocket accelerates in space because it pushes mass at high speed out the end of the engine in the form of exhaust gases from burning fuel. The forward momentum of a rocket is equal to, but in the opposite direction from, the momentum of the escaping mass ejected from the end of the engine.

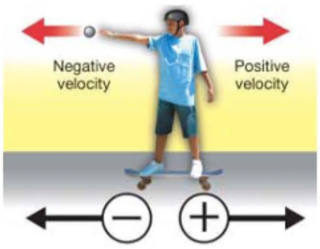


Figure 6.15: *The direction is important when using the law of conservation of momentum. We use positive and negative numbers to represent opposite directions.*

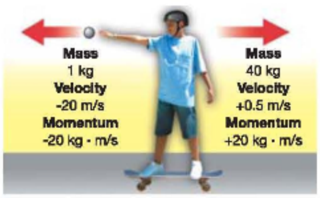


Figure 6.16: *The result of a skateboarder throwing a 1-kg ball at a velocity of –20 m/s is that he and the skateboard with a total mass of 40 kg move backward at a velocity of +0.5 m/s if you ignore friction. If you account for friction, would the calculation for velocity of the skateboarder on the skateboard end up being less or more than 0.5 m/s?*

Solving Problems: Conservation of Momentum

An astronaut in space throws a 2-kilogram wrench away from her at a velocity of –10 m/s. If the astronaut's mass is 100 kilograms, at what velocity does the astronaut move backward after throwing the wrench?

1. Looking for: You are asked for the astronaut's speed. Since the astronaut is in space, we can ignore friction.

2. Given: You are given the mass and velocity of the wrench and the mass of the astronaut.

3. Relationships: This is enough information to apply the law of conservation of momentum. The momentum of the wrench (m_1v_1) and the momentum of the astronaut (m_2v_2) add up to zero BEFORE the wrench is thrown.
$m_1 v_1 + m_2 v_2 = 0$

Photo courtesy NASA

4. Solution: The momentum of the wrench and the astronaut also add up to zero AFTER the wrench is thrown.
$[2\text{ kg} \times (-10\text{ m/s})] + [(100\text{ kg}) \times v_2] = 0$; $v_2 = +20 \div 100 = +0.2$ m/s

The astronaut moves backward at a velocity of +0.2 m/s to the right.

Your turn...

a. Two hockey players have a total momentum of +200 kg·m/s before a collision (+ is to the right). After their collision, they move together. In what direction do they move and what is their momentum?

b. When a large truck hits a small car, the forces are equal (Figure 6.17). However, the small car experiences a much greater change in velocity than the big truck. Explain why.

Figure 6.17: *Your turn... Question b.*

SOLVE FIRST LOOK LATER

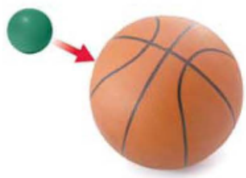
a. The two hockey players move in the positive direction (or to the right). Their momentum after the collision is +200 kg·m/s.

b. The car has less mass and therefore less inertia, so it accelerates more (and may become more damaged) than the truck in this collision.

Section 6.3 Review

1. Emilio tries to jump to a nearby dock from a canoe that is floating in the water. Instead of landing on the dock, he falls into the water beside the canoe. Use Newton's third law to explain why this happened. Hint: First identify the action–reaction pair in this example.
2. You push backward against the ground to move a skateboard forward. The force you make acts against the ground. What force acts against you to move you forward?
3. Explain why action–reaction forces do NOT cancel each other out, resulting in zero net force.
4. The momentum of an object depends on what two factors?
5. The engine of a jet airplane pushes exhaust gases from burning fuel backward. What pushes the jet forward?

6. A small rubber ball is thrown at a heavier, larger basketball that is not moving. The small ball bounces off the basketball. Assume there are no outside forces acting on the balls.
   a. How does the force on the small ball compare to the force on the basketball?
   b. Compare the total momentum of the two balls before and after the collision.
   c. The mass of the basketball is 600 grams and its velocity before the small ball hits is 0 m/s. The mass of the small ball is 100 grams and its velocity is +5 m/s before the collision and –4 m/s afterward. What is the velocity of the basketball after the collision?



SCIENCE FACT

Squid Science

Airplanes are not the only things that use jet propulsion. Several animals have adapted jet propulsion in order to get around. A squid takes water into its body chamber and rapidly pushes it out of a backward-facing tube. The water squirts backward and the squid jets forward. What are the action–reaction forces in this example? Draw a diagram to illustrate your answer.

Most species of squid are small, but *Architeuthis*, the giant squid, is not! In September 2004, Japanese scientists took over 500 photos of a giant squid. The animal was nearly 25 feet long! This was the first record of a live giant squid in the wild. Conduct an Internet search using the key phrase "giant squid" to find more information and photos.