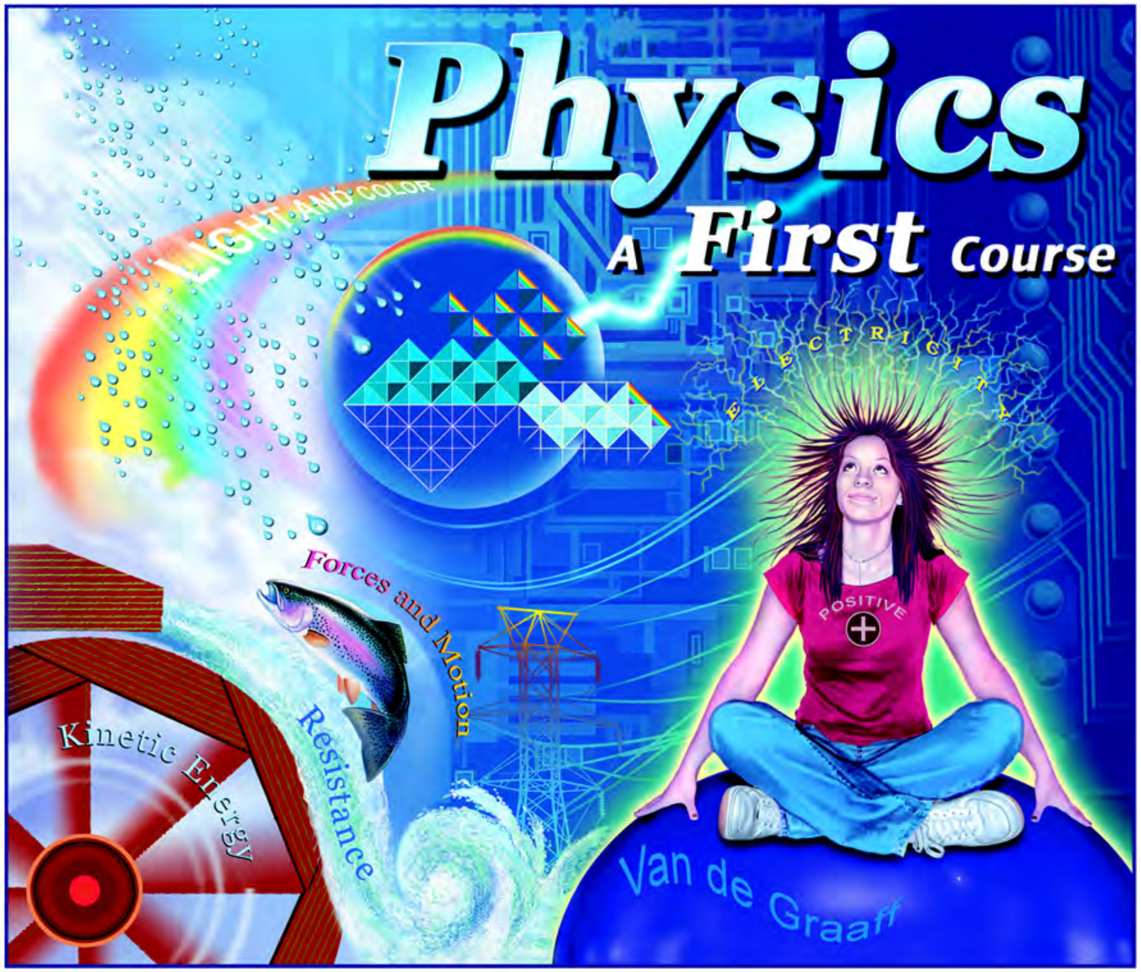
Physics

A First Course



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About the Author

Dr. Thomas C. Hsu is a nationally recognized innovator in science and math education and the founder of CPO Science (formerly Cambridge Physics Outlet). He holds a Ph.D. in Applied Plasma Physics from the Massachusetts Institute of Technology (MIT), and has taught students from elementary, secondary and college levels across the nation. He was nominated for MIT's Goodwin medal for excellence in teaching and has received numerous awards from various state agencies for his work to improve science education. Tom has personally worked with more than 12,000 K-12 teachers and administrators and is well known as a consultant, workshop leader and developer of curriculum and equipment for inquiry-based learning in science and math. With CPO Science, Tom has published textbooks in physical science, integrated science, and also written fifteen curriculum Investigation guides that accompany CPO Science equipment. Along with the CPO Science team, Tom is always active, developing innovative new tools for teaching and learning science, including an inquiry-based chemistry text.

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Chapter 3

Conservation Laws

Look around you. Do you see any changes taking place? Is a light bulb giving off heat and light? Is the sun shining? Are your eyes moving across the page while you read this introduction? When an object falls toward Earth, when you play a sport or a musical instrument, when your alarm clock wakes you up in the morning, and when a bird flies through the air, there are changes taking place that could not occur without the effects of *energy*.

Energy is everywhere! Energy is responsible for explaining "how the world works". As you read this chapter think about the examples and see if you can identify the forms of energy that are responsible for the changes that take place in each. Skateboarding, astronauts, car crashes, ball throwing, billiards, and tennis are just some of the physical systems you will encounter. Studying physics also requires energy, so always eat a good breakfast!

Key Questions

- ✓ Do objects at rest ever have any forces acting on them?
- ✓ Why does a faster skateboarder take more force to stop than a slower one with the same mass?
- ✓ How can energy be so important when it cannot be smelled, touched, tasted, seen, or heard?

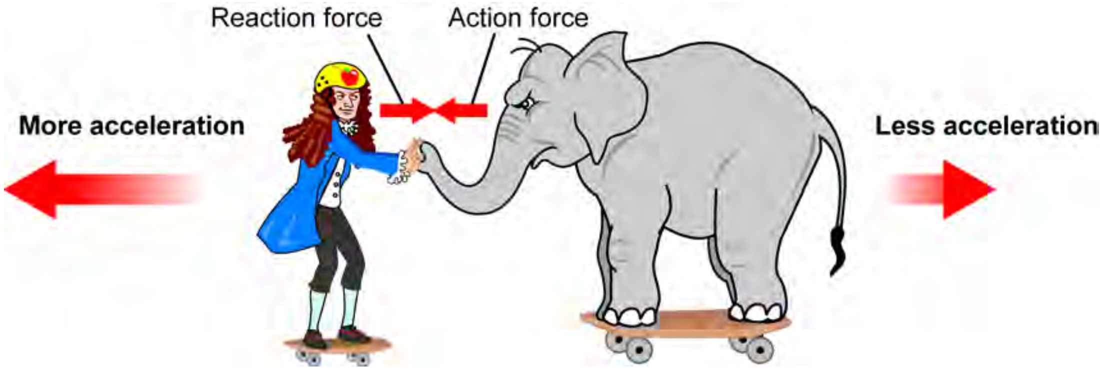
3.1 Newton's Third Law and Momentum

For every action there is an equal and opposite reaction. This section is about the true meaning of this statement, known as Newton's third law of motion. In the last section, you learned that forces cause changes in motion. However, this does not mean that objects at rest experience no forces! What is that keeps your book perfectly still on the table as you read it even though you *know* gravity exerts a force on the book (Figure 3.1)? "Force" is a good answer to this question and the third law is the key to understanding why.

Newton on a skateboard

An imaginary skateboard contest

Imagine a skateboard contest between Newton and an elephant. They can only push against each other, not against the ground. The fastest one wins. The elephant knows it is much stronger and pushes off Newton with a huge force thinking it will surely win. But who does win?



The winner

Newton wins — and will always win. No matter how hard the elephant pushes, Newton always moves away at a greater speed. In fact, Newton doesn't have to push at all and he still wins. Why?

Forces always come in pairs

You already know 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. Since the action and reaction forces are equal in strength and because of Newton's second law of motion ($a = F/m$), Newton accelerates more because his mass is smaller.

Vocabulary

Newton's third law, momentum, impulse, law of conservation of momentum

Objectives

- ✓ Use Newton's third law to explain various situations.
- ✓ Explain the relationship between Newton's third law and momentum conservation.
- ✓ Solve recoil problems.

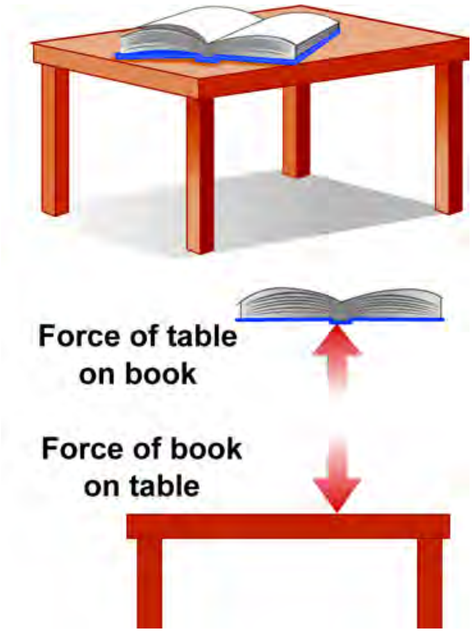


Figure 3.1: *There are forces acting even when things are not moving.*

The third law of motion

The first and second laws

The first and second laws of motion apply to single objects. The first law says an object will remain at rest or in motion at constant velocity unless acted upon by a net force. The second law says the acceleration of an object is directly proportional to force and inversely proportional to the mass ($a = F/m$).

The third law operates with pairs of objects

In contrast to the first two laws, 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.

> For every action force, there is a reaction force equal in strength and opposite in direction.

Forces *only* come in action-reaction pairs. There can never be a single force, alone, without its action-reaction partner. The force exerted by the elephant (action) moves Newton since it acts on Newton. The reaction force acting back on the elephant is what moves the elephant.

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 reaction. You choose one to call the action and then call the other one the reaction (Figure 3.2).

A skateboard example

Think carefully about moving the usual way on a skateboard. Your foot exerts a force backward against the ground. The force acts *on* the ground. However, *you* move, so a force must act on you. 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* (Figure 3.3).

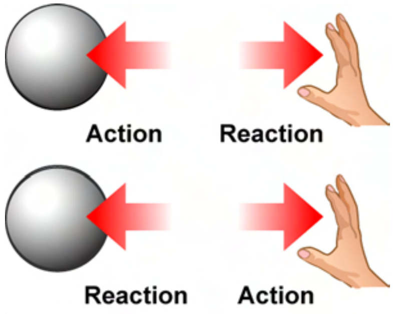


Figure 3.2: *It doesn't matter which force you call the action and which the reaction. The action and reaction forces are interchangeable.*

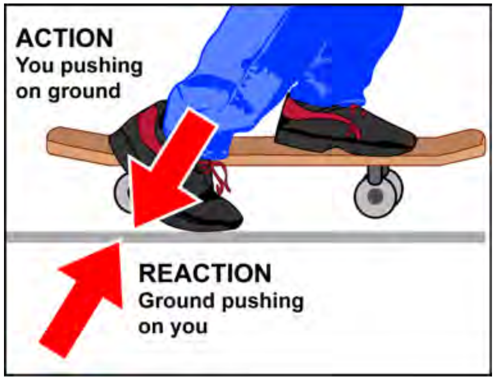


Figure 3.3: *All forces come in pairs. When you push on the ground (action), the reaction of the ground pushing back on your foot is what makes you move.*

Action and reaction forces

Action and reaction forces do not cancel

It is easy to get confused thinking about action and reaction forces. Why don't they cancel each other out? The reason is that action and reaction forces act on different objects. For example, think 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 because they act on different objects. You can only cancel forces if they act on the same object (Figure 3.4).

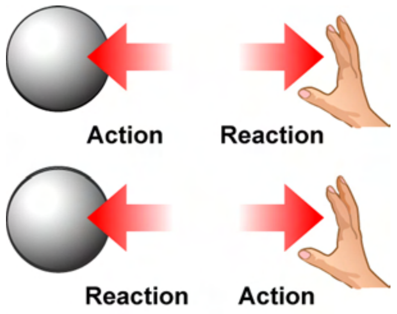


Figure 3.4: *An example diagram showing the action and reaction forces in throwing a ball.*

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.

Identifying action and reaction

Here are some guidelines to help you sort out action and reaction forces:

- Both are always there whenever any force appears.
- They always have the exact same strength.
- They always act in opposite directions.
- They always act on different objects.
- Both are real forces and either (or both) can cause acceleration.

Action and reaction

A woman with a weight of 500 N is sitting on a chair. Describe an action-reaction pair of forces.

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

2. Given: You are given one force in newtons.

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

4. Solution: The force of 500 N exerted by the woman on the chair seat is an action. The chair seat acting on the woman with an upward force of 500 N is a reaction.

Your turn...

a. A baseball player hits a ball with a bat. Describe an action-reaction pair of forces. **Answer:** The force of the bat on the ball accelerates the ball. The force of the ball on the bat (reaction) slows down the swinging bat (action).

b. Earth and its moon are linked by an action-reaction pair. **Answer:** Earth attracts the moon (action) and the moon attracts Earth (reaction) in an action-reaction pair. Both action and reaction are due to gravity.

Momentum

Faster objects are harder to stop

Imagine two kids on skateboards are moving toward you (Figure 3.5). Each has a mass of 40 kilograms. One is moving at one meter per second and the other at 10 meters per second. Which one is harder to stop?

You already learned that inertia comes from mass. That explains why an 80-kilogram skateboarder is harder to stop than a 40-kilogram skateboarder. But how do you account for the fact that a faster skateboarder takes more force to stop than a slower one with the *same* mass?

Momentum

The answer is a new quantity called **momentum.** The momentum of a moving object is its mass multiplied by its velocity. Like inertia, momentum measures a moving object's resistance to changes in its motion. However, momentum includes the effects of speed and direction as well as mass. The symbol *p* is used to represent momentum.

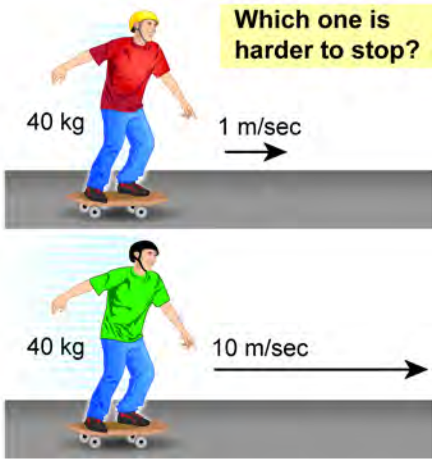


Figure 3.5: *Stopping a fast-moving object is harder than stopping a slow-moving on.*

MOMENTUM

$$\textit{Momentum}\ (\text{kg·m/sec}) \longrightarrow p = \overset{\textit{Mass}\ (\text{kg})}{m}\,v \longleftarrow \textit{Velocity}\ (\text{m/sec})$$

Units of momentum

The units of momentum are the units of mass multiplied by the units of velocity. When mass is in kilograms and velocity is in meters per second, momentum is in kilogram·meters per second (kg·m/sec).

Calculating momentum

Momentum is calculated with velocity instead of speed because the direction of momentum is always important. A common choice is to make positive momentum to the right and negative momentum to the left (Figure 3.6).

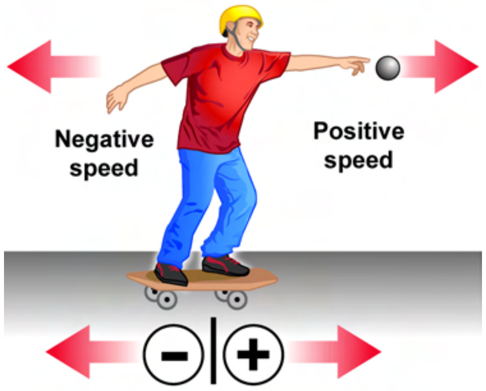
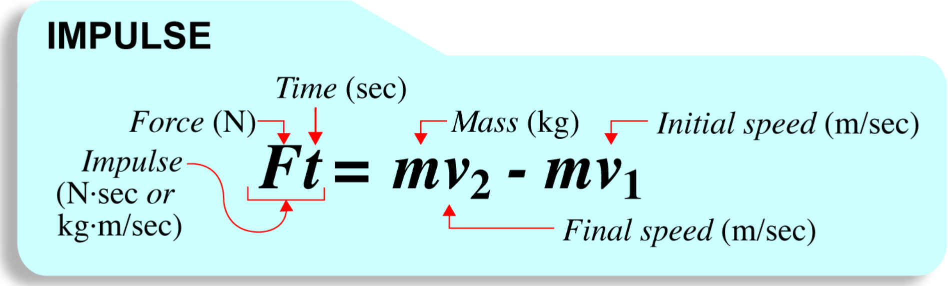


Figure 3.6: *The direction is important when calculating momentum. We use positive and negative numbers to represent opposite directions.*

Impulse

Force changes momentum Momentum changes when velocity changes. Since force is what changes velocity, that means that force is also linked to changes in momentum. The relationship with momentum gives us an important new way to look at force.

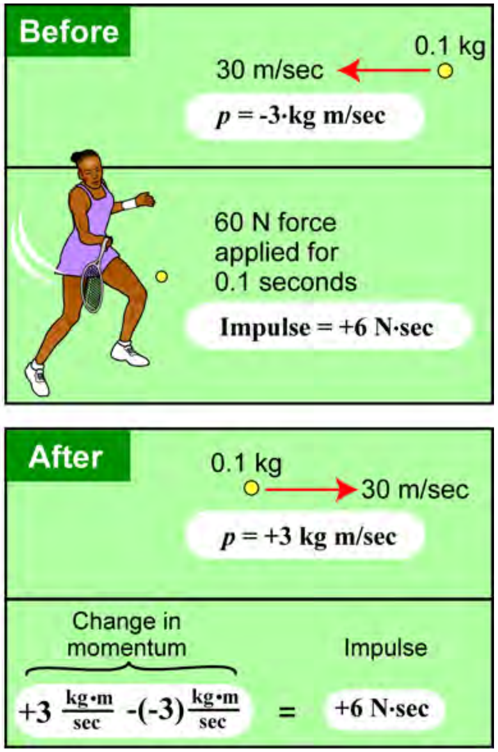
Impulse A change in an object’s momentum depends on the net force and also on the amount of time the force is applied. The change in momentum is equal to the net force multiplied by the time the force acts. A change in momentum created by a force exerted over time is called **impulse**.



IMPULSE

$$Ft = mv_2 - mv_1$$

Units of impulse Notice that the force side of the equation has units of N·sec, while the momentum side has units of momentum, kg·m/sec. These are the same units, since 1 N is 1 kg·m/s^2. Impulse can be correctly expressed either way.



Force and momentum

A net force of 100 N is applied for 5 seconds to a 10-kg car that is initially at rest. What is the speed of the car at the end of the 5 seconds.

1. Looking for: You are asked for the speed.

2. Given: You are given the net force in newtons, the time the force acts in seconds, and the mass of the car in kilograms.

3. Relationships: impulse = force × time = change in momentum; momentum = mass × velocity.

4. Solution: The car’s final momentum = 100 N × 5 seconds = 500 kg·m/sec.
Speed is momentum divided by mass, or v = (500 kg·m/sec) ÷ 10 kg = 50 m/sec

Your turn...

a. A 15-N force acts for 10 seconds on a 1-kg ball initially at rest. What is the ball’s final momentum? **Answer:** 150 kg·m/sec

b. How much time should a 100-N force take to increase the speed of a 10-kg car from 10 m/sec to 100 m/sec? **Answer:** 9 sec

The law of momentum conservation

An important new law

We are now going to combine Newton's third law with the relationship between force and momentum. The result is a powerful new tool for understanding motion: the law of conservation of momentum. This law allows us to make accurate predictions about what happens before and after an interaction even if we don't know the details about the interaction itself.

Momentum in an action-reaction pair

When two objects exert forces on each other in an action-reaction pair, their motions are affected as a pair. If you stand on a skateboard and throw a bowling ball, you apply force to the ball. That force changes the momentum of the ball.

The third law says the ball exerts an equal and opposite force back on you. Therefore, *your* momentum also changes. Since the forces are exactly equal and opposite, the changes in momentum are also equal and opposite. If the ball gains +20 kg·m/sec of forward momentum, you must gain -20 kg·m/sec of backward momentum (Figure 3.7).

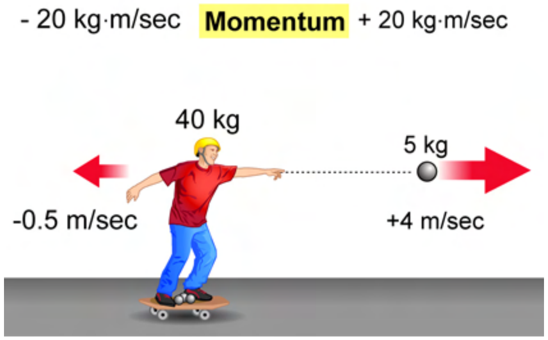


Figure 3.7: *The result of the skateboarder throwing a 1-kg ball at a speed of 20 m/sec is that he and the board, with a total mass of 40 kg, move backward at a speed of -0.5 m/sec, if you ignore friction.*

The law of conservation of momentum

Because of the third law, the total momentum of two interacting objects stays constant. If one gains momentum, the other loses the same amount, leaving the total unchanged. This is the **law of conservation of momentum**. The law says the total momentum in a system of interacting objects cannot change as long all forces act only between the objects in the system.

> If interacting objects in a system are not acted on by outside forces, the total amount of momentum in the system cannot change.

Forces inside and outside the system

Forces outside the system, such as friction and gravity, can change the total momentum of the system. However, if ALL objects that exert forces are included in the system, the total momentum stays perfectly constant. When you jump up, the reaction force from the ground gives you upward momentum. The action force from your feet gives the *entire Earth* an equal amount of downward momentum and the universe keeps perfect balance. No one notices the planet move because it has so much more mass than you so its increase in momentum creates negligible velocity (Figure 3.8).

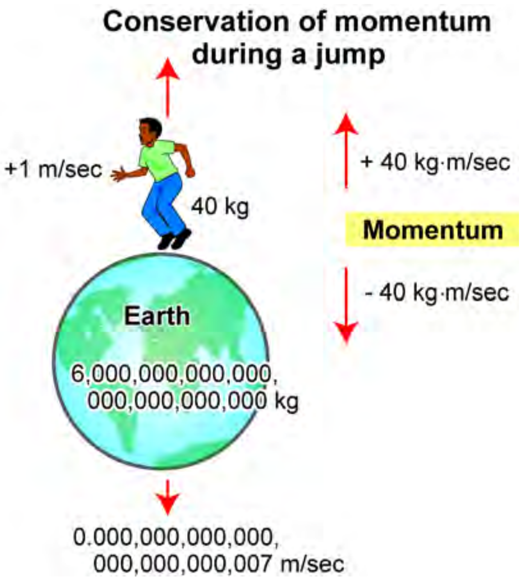
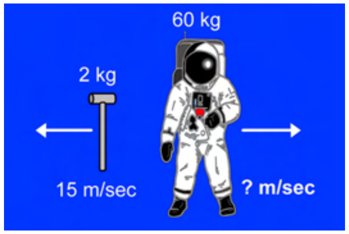


Figure 3.8: *When you jump, your body and Earth gain equal and opposite amounts of momentum.*

Using the momentum relationship

An astronaut floating in space throws a 2-kilogram hammer to the left at 15 m/sec. If the astronaut's mass is 60 kilograms, how fast does the astronaut move to the right after throwing the hammer?



1. Looking for: You are asked for the speed of the astronaut after throwing the hammer.

2. Given: You are given the mass of the hammer in kilograms and the speed of the hammer in m/sec and the mass of the astronaut in kilograms.

3. Relationships: The total momentum before the hammer is thrown must be the same as the total after. Momentum = mass × velocity. A negative sign indicates the direction of motion is to the left.

4. Solution: Both the astronaut and hammer were initially at rest, so the initial momentum was zero. Use subscripts (*a* and *h*) to distinguish between the astronaut and the hammer.
$m_a v_a + m_h v_h = 0$

Plug in the known numbers:
$(60\text{ kg})(v_a) + (2\text{ kg})(-15\text{ m/sec}) = 0$

Solve:
$(60\text{ kg})(v_a) = +30\text{ kg·m/sec}$
$v_a = +0.5\text{ m/sec}$ The astronaut moves to the right at a speed of 0.5 m/sec.

Your turn...

a. Two children on ice skates start at rest and push off from each other. One has a mass of 30 kg and moves back at 2 m/sec. The other has a mass of 15 kg. What is the second child's speed? **Answer:** 4 m/sec

b. Standing on an icy pond, you throw a 0.5 kg ball at 40 m/sec. You move back at 0.4 m/sec. What is your mass? **Answer:** 50 kg

3.1 Section Review

1. List three action and reaction pairs shown in the picture at right.
2. Why don't action and reaction forces cancel?
3. Use impulse to explain how force is related to changes in momentum.
4. Explain the law of conservation of momentum and how it relates to Newton's third law.