KEY CONCEPT

2.2 Force and mass determine acceleration.

BEFORE, you learned

- Mass is a measure of inertia
- The motion of an object will not change unless the object is acted upon by an unbalanced force

NOW, you will learn

- How Newton's second law relates force, mass, and acceleration
- How force works in circular motion

VOCABULARY

Newton's second law p. 50
centripetal force p. 54

EXPLORE Acceleration

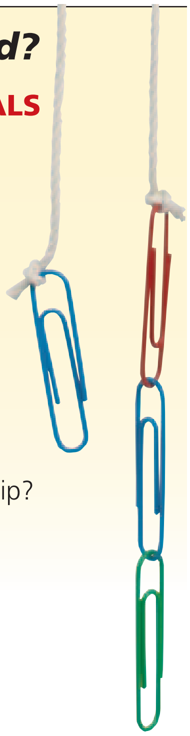
How are force and acceleration related?

PROCEDURE

1. Tie a paper clip to each end of a long string. Hook two more paper clips to one end.
2. Hold the single paper clip in the middle of a smooth table; hang the other end of the string over the edge. Let go and observe.
3. Add one more paper clip to the hanging end and repeat the experiment. Observe what happens. Repeat.

MATERIALS

- paper clips
- string



WHAT DO YOU THINK?

- What happened each time that you let go of the single paper clip?
- Explain the relationship between the number of hanging paper clips and the motion of the paper clip on the table.

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

Suppose you are eating lunch with a friend and she asks you to pass the milk container. You decide to slide it across the table to her. How much force would you use to get the container moving? You would probably use a different force if the container were full than if the container were empty.

If you want to give two objects with different masses the same acceleration, you have to apply different forces to them. You must push a full milk container harder than an empty one to slide it over to your friend in the same amount of time.

REMINDER
Acceleration is a change in velocity over time.

CHECK YOUR READING What three concepts are involved in Newton's second law?

Newton's Second Law

SIMULATION
CLASSZONE.COM
Explore Newton's second law.

Newton studied how objects move, and he noticed some patterns. He observed that the acceleration of an object depends on the mass of the object and the size of the force applied to it. **Newton's second law** states that the acceleration of an object increases with increased force and decreases with increased mass. The law also states that the direction in which an object accelerates is the same as the direction of the force.

The photographs below show Newton's second law at work in a supermarket. The acceleration of each shopping cart depends upon two things:

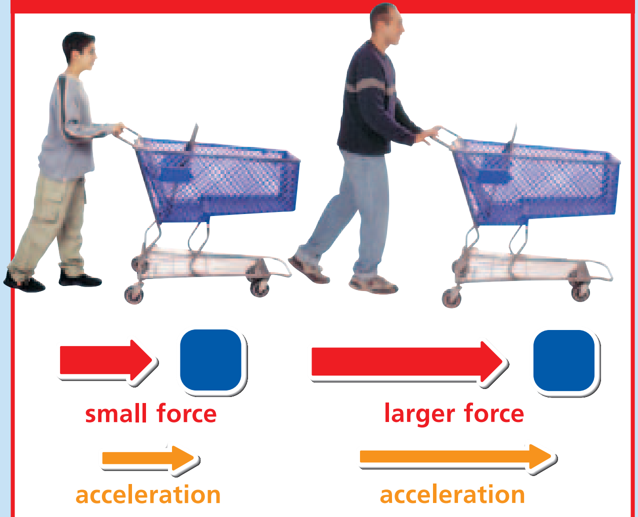
- the size of the force applied to the shopping cart
- the mass of the shopping cart

In the left-hand photograph, the force on the cart changes, while the mass of the cart stays the same. In the right-hand photograph, the force on the cart stays the same, while the mass of the cart varies. Notice how mass and force affect acceleration.

Newton's Second Law

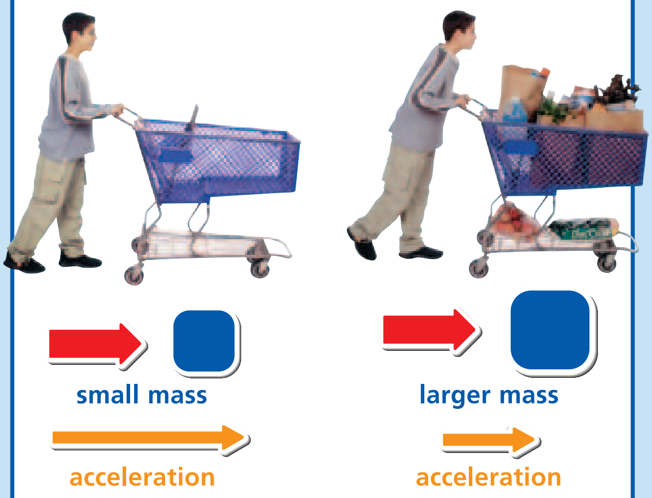
The acceleration of an object increases with increased force, decreases with increased mass, and is in the same direction as the force.

Increasing Force Increases Acceleration



The force exerted on the cart by the man is greater than the force exerted on the same cart by the boy, so the acceleration is greater.

Increasing Mass Decreases Acceleration



The mass of the full cart is greater than the mass of the empty cart, and the boy is pushing with the same force, so the acceleration is less.

READING VISUALS What do the arrows in these diagrams show?

Force Equals Mass Times Acceleration

Newton was able to describe the relationship of force, mass, and acceleration mathematically. You can calculate the force, the mass, or the acceleration if you know two of the three factors. The mathematical form of Newton's second law, stated as a formula, is

$$\textbf{Force} = \textbf{mass} \cdot \textbf{acceleration}$$
$$F = ma$$

To use this formula, you need to understand the unit used to measure force. In honor of Newton's contribution to our understanding of force and motion, the standard unit of force is called the newton (N). Because force equals mass times acceleration, force is measured in units of mass (kilograms) times units of acceleration (meters per second per second). A newton is defined as the amount of force that it takes to accelerate one kilogram (1 kg) of mass one meter per second per second (1 m/s^2). So 1 N is the same as 1 kg • m/s^2.

REMINDER

Meters per second per second is the same as *m/s*^{2}, which can be read "meters per second squared."

CHECK YOUR READING If the same force is applied to two objects of different mass, which object will have the greater acceleration?

The mathematical relationship of force, mass, and acceleration allow you to solve problems about how objects move. If you know the mass of an object and the acceleration you want to achieve, you can use the equation to find the force you need to exert to produce that acceleration. Use Newton's second law to find the force that is needed to accelerate the shopping cart in the sample problem.

Calculating Force

Sample Problem

What force is needed to accelerate a 10 kg shopping cart 3 m/s^2?

What do you know? mass = 10 kg, acceleration = 3 m/s^2

What do you want to find out? Force

Write the formula: $F = ma$

Substitute into the formula: $F = 10\ \text{kg} \cdot 3\ \text{m/s}^2$

Calculate and simplify: $F = 10\ \text{kg} \cdot \frac{3\text{m}}{\text{s}^2} = 30\ \text{kg} \cdot \text{m/s}^2$

Check that your units agree: Unit is kg • m/s^2.
Unit of force is newton, which is also kg • m/s^2. Units agree.

Answer: $F = 30$ N

Practice the Math

1. If a 5 kg ball is accelerating 1.2 m/s^2, what is the force on it?
2. A person on a scooter is accelerating 2 m/s^2. If the person has a mass of 50 kg, how much force is acting on that person?

This team of 20 people pulled a 72,000-kilogram (159,000 lb) Boeing 727 airplane 3.7 meters (12 ft) in 6.74 seconds.

The photograph above shows people who are combining forces to pull an airplane. Suppose you knew the mass of the plane and how hard the people were pulling. How much would the plane accelerate? The sample problem below shows how Newton's second law helps you calculate the acceleration.

Calculating Acceleration

Sample Problem

If a team pulls with a combined force of 9000 N on an airplane with a mass of 30,000 kg, what is the acceleration of the airplane?

What do you know? mass = 30,000 kg, force = 9000 N

What do you want to find out? acceleration

Rearrange the formula: $a = \frac{F}{m}$

Substitute into the formula: $a = \frac{9000\ \text{N}}{30{,}000\ \text{kg}}$

Calculate and simplify: $a = \frac{9000\ \text{N}}{30{,}000\ \text{kg}} = \frac{9000\ \text{kg} \cdot \text{m/s}^2}{30{,}000\ \text{kg}} = 0.3\ \text{m/s}^2$

Check that your units agree: Unit is m/s^2.
Unit for acceleration is m/s^2.
Units agree.

Answer: $a = 0.3\ \text{m/s}^2$

Practice the Math

1. Half the people on the team decide not to pull the airplane. The combined force of those left is 4500 N, while the airplane's mass is still 30,000 kg. What will be the acceleration?
2. A girl pulls a wheeled backpack with a force of 3 N. If the backpack has a mass of 6 kg, what is its acceleration?

Mass and Acceleration

Mass is also a variable in Newton's second law. If the same force acts on two objects, the object with less mass will have the greater acceleration. For instance, if you push a soccer ball and a bowling ball with equal force, the soccer ball will have a greater acceleration.

If objects lose mass, they can gain acceleration if the force remains the same. When a rocket is first launched, most of its mass is the fuel it carries. As the rocket burns fuel, it loses mass. As the mass continually decreases, the acceleration continually increases.

APPLY This NASA launch rocket accelerates with enough force to lift about 45 cars off the ground. As the rocket loses fuel, will it accelerate more or less? Why?

Calculating Mass

Sample Problem

A model rocket is accelerating at 2 m/s². The force on it is 1 N. What is the mass of the rocket?

What do you know? acceleration = 2 m/s², force = 1 N

What do you want to find out? mass

Rearrange the formula: $m = \frac{F}{a}$

Substitute into the formula: $m = \frac{1\ \text{N}}{2\ \text{m/s}^2}$

Calculate and simplify: $m = \frac{1\ \text{N}}{2\ \text{m/s}^2} = \frac{1\ \text{kg} \cdot \text{m/s}^2}{2\ \text{m/s}^2} = 0.5\ \text{kg}$

Check that your units agree: Unit is kg.
Unit of mass is kg. Units agree.

Answer: m = 0.5 kg

Practice the Math

1. Another model rocket is accelerating at a rate of 3 m/s² with a force of 1 N. What is the mass of the rocket?
2. A boy pushes a shopping cart with a force of 10 N, and the cart accelerates 1 m/s². What is the mass of the cart?

Forces can change the direction of motion.

Usually, we think of a force as either speeding up or slowing down the motion of an object, but force can also make an object change direction. If an object changes direction, it is accelerating. Newton's second law says that if you apply a force to an object, the direction in which the object accelerates is the same as the direction of the force. You can change the direction of an object without changing its speed. For example, a good soccer player can control the motion of a soccer ball by applying a force that changes the ball's direction but not its speed.

CHECK YOUR READING How can an object accelerate when it does not change speed?

INVESTIGATE Motion and Force

What affects circular motion?

SKILL FOCUS
Hypothesizing

PROCEDURE

1. Spread newspaper over your work surface. Place the paper plate down on the newspaper.
2. Practice rolling the marble around the edge of the plate until you can roll it around completely at least once.
3. Cut out a one-quarter slice of the paper plate. Put a dab of paint on the edge of the plate where the marble will leave it. Place the plate back down on the newspaper.
4. Hypothesize: How will the marble move once it rolls off the plate? Why?
5. Roll the marble all the way around the paper plate into the cut-away section and observe the resulting motion as shown by the trail of paint.

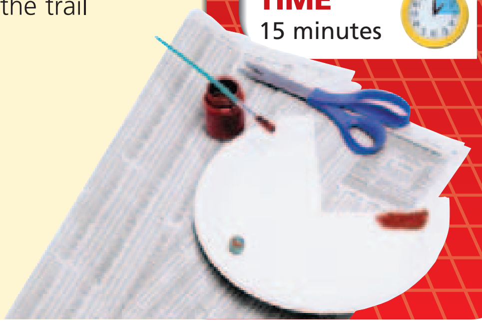
WHAT DO YOU THINK?

- Did your observations support your hypothesis?
- What forces affected the marble's motion after it left the plate?

CHALLENGE How will changing the speed at which you roll the marble change your results? Repeat the activity to test your prediction.

MATERIALS
- newspaper
- paper plate
- marble
- scissors
- poster paint
- paintbrush

TIME
15 minutes

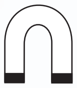


Centripetal Force

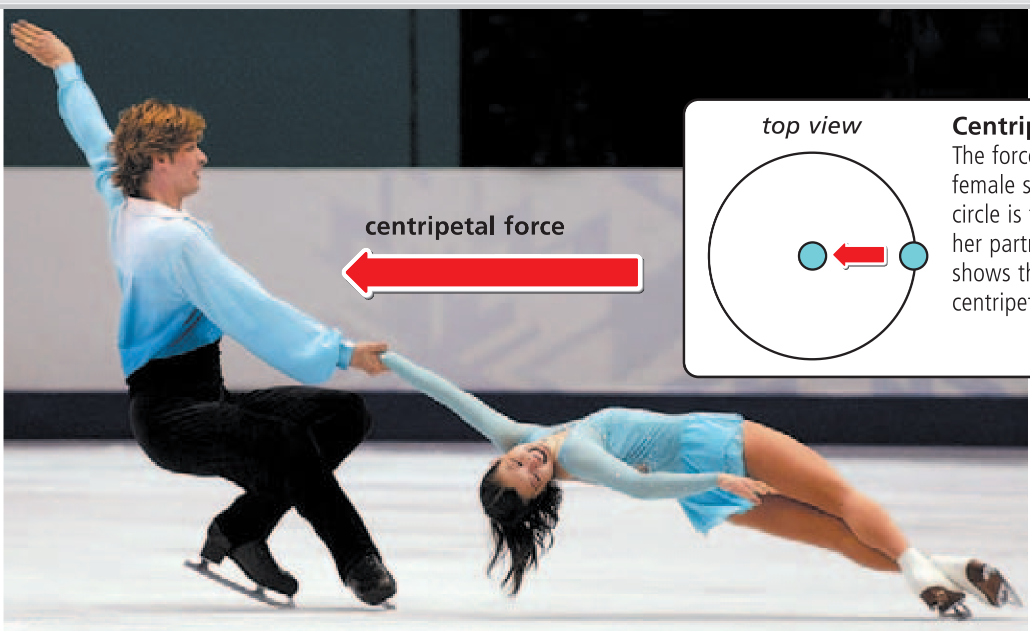
When you were younger, you may have experimented with using force to change motion. Perhaps you and a friend took turns swinging each other in a circle. If you remember this game, you may also remember that your arms got tired because they were constantly pulling your friend as your friend spun around. It took force to change the direction of your friend's motion. Without that force, your friend could not have kept moving in a circle.

Any force that keeps an object moving in a circle is known as a **centripetal force** (sehn-TRIHP-ih-tuhl). This force points toward the center of the circle. Without the centripetal force, the object would go flying off in a straight line. When you whirl a ball on a string, what keeps the ball moving in a circle? The force of the string turns the ball, changing the ball's direction of motion. When the string turns, so does the ball. As the string changes direction, the force from the string also changes direction. The force is always pointing along the string toward your hand, the center of the circle. The centripetal force on the whirling ball is the pull from the string. If you let go of the string, the ball would fly off in the direction it was headed when you let go.

VOCABULARY
Remember to make a magnet word diagram for *centripetal force*.



CHECK YOUR READING How does centripetal force change the motion of an object?



Centripetal force The force that keeps the female skater moving in a circle is the pull exerted by her partner. The diagram shows the direction of the centripetal force.

Circular Motion and Newton's Second Law

Suppose the male skater shown above spins his partner faster. Her direction changes more quickly than before, so she accelerates more. To get more acceleration, he must apply more force. The same idea holds for a ball you whirl on a string. You have to pull harder on the string when you whirl the ball faster, because it takes more centripetal force to keep the ball moving at the greater speed.

You can apply the formula for Newton's second law even to an object moving in a circle. If you know the size of the centripetal force acting upon the object, you can find its acceleration. A greater acceleration requires a greater centripetal force. A more massive object requires a greater centripetal force to have the same circular speed as a less massive object. But no matter what the mass of an object is, if it moves in a circle, its force and acceleration are directed toward the center of the circle.

CHECK YOUR READING How does increasing the centripetal force on an object affect its acceleration?

2.2 Review

KEY CONCEPTS

1. If the force acting upon an object is increased, what happens to the object's acceleration?
2. How does the mass of an object affect its acceleration?
3. What force keeps an object moving in a circle? In what direction does this force act?

CRITICAL THINKING

4. **Infer** Use Newton's second law to determine how much force is being applied to an object that is traveling at a constant velocity.
5. **Calculate** What force is needed to accelerate an object 5 m/s^2 if the object has a mass of 10 kg?

CHALLENGE

6. **Synthesize** Carlos pushes a 3 kg box with a force of 9 N. The force of friction on the box is 3 N in the opposite direction. What is the acceleration of the box? **Hint:** Combine forces to find the net force.