CHAPTER 12

Newton’s Second Law

**What You’ll Learn**
- **Explain** Newton’s second law of motion.
- **Explain** why the direction of force is important.

**Why It’s Important**
Newton’s second law of motion explains how any object, from a swimmer to a satellite, moves when acted on by forces.

**Review Vocabulary**
- acceleration: the change in velocity divided by the time over which the change occurred

**New Vocabulary**
- Newton’s second law of motion
- weight
- center of mass

**Force and Acceleration**

When you go shopping in a grocery store and push a cart, you exert a force to make the cart move. If you want to slow down or change the direction of the cart, a force is required to do this, as well. Would it be easier for you to stop a full or empty grocery cart suddenly, as in **Figure 7**? When the motion of an object changes, the object is accelerating. Acceleration occurs any time an object speeds up, slows down, or changes its direction of motion. Newton’s second law describes how forces cause an object’s motion to change.

**Newton’s second law of motion** connects force, acceleration, and mass. According to the second law of motion, an object acted upon by a force will accelerate in the direction of the force. The acceleration is given by the following equation:

\[ a = \frac{F_{\text{net}}}{m} \]

In this equation, \( a \) is the acceleration, \( m \) is the mass, and \( F_{\text{net}} \) is the net force. If both sides of the above equation are multiplied by the mass, the equation can be written this way:

\[ F_{\text{net}} = ma \]

**Reading Check**

What is Newton’s second law?

**Figure 7** The force needed to change the motion of an object depends on its mass. **Predict** which grocery cart would be easier to stop.
Units of Force  Force is measured in newtons, abbreviated N. Because the SI unit for mass is the kilogram (kg) and acceleration has units of meters per second squared (m/s²), 1 N also is equal to 1 kg·m/s². In other words, to calculate a force in newtons from the equation shown on the prior page, the mass must be given in kg and the acceleration in m/s².

Gravity

One force that you are familiar with is gravity. Whether you’re coasting down a hill on a bike or a skateboard or jumping into a pool, gravity is at work pulling you downward. Gravity also is the force that causes Earth to orbit the Sun and the Moon to orbit Earth.

What is gravity?  The force of gravity exists between any two objects that have mass. Gravity always is attractive and pulls objects toward each other. A gravitational attraction exists between you and every object in the universe that has mass. However, the force of gravity depends on the mass of the objects and the distance between them. The gravitational force becomes weaker the farther apart the objects are and also decreases as the masses of the objects involved decrease.

For example, there is a gravitational force between you and the Sun and between you and Earth. The Sun is much more massive than Earth, but is so far away that the gravitational force between you and the Sun is too weak to notice. Only Earth is close enough and massive enough to exert a noticeable gravitational force on you. The force of gravity between you and Earth is about 1,650 times greater than between you and the Sun.

Weight  The force of gravity causes all objects near Earth’s surface to fall with an acceleration of 9.8 m/s². By Newton’s second law, the gravitational force on any object near Earth’s surface is:

\[ F = ma = m \times (9.8 \text{ m/s}^2) \]

This gravitational force also is called the weight of the object. Your weight on Earth is the gravitational force between you and Earth. Your weight would change if you were standing on a planet other than Earth, as shown in Table 1. Your weight on a different planet would be the gravitational force between you and the planet.

<table>
<thead>
<tr>
<th>Place</th>
<th>Weight in Newtons If Your Mass Were 60 kg</th>
<th>Percent of Your Weight on Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mars</td>
<td>221</td>
<td>37.6</td>
</tr>
<tr>
<td>Earth</td>
<td>588</td>
<td>100.0</td>
</tr>
<tr>
<td>Jupiter</td>
<td>1,387</td>
<td>235.9</td>
</tr>
<tr>
<td>Pluto</td>
<td>39</td>
<td>6.6</td>
</tr>
</tbody>
</table>

Newton and Gravity  Isaac Newton was the first to realize that gravity—the force that made objects fall to Earth—was also the force that caused the Moon to orbit Earth and the planets to orbit the Sun. In 1687, Newton published a book that included the law of universal gravitation. This law showed how to calculate the gravitational force between any two objects. Using the law of universal gravitation, astronomers were able to explain the motions of the planets in the solar system, as well as the motions of distant stars and galaxies.
Weight and Mass  Weight and mass are different. Weight is a force, just like the push of your hand is a force, and is measured in newtons. When you stand on a bathroom scale, you are measuring the pull of Earth’s gravity—a force. However, mass is the amount of matter in an object, and doesn’t depend on location. Weight will vary with location, but mass will remain constant. A book with a mass of 1 kg has a mass of 1 kg on Earth or on Mars. However, the weight of the book would be different on Earth and Mars. The two planets would exert a different gravitational force on the book.

Using Newton’s Second Law  How does Newton’s second law determine how an object moves when acted upon by forces? The second law tells how to calculate the acceleration of an object if its mass and the forces acting on it are known. You may remember that the motion of an object can be described by its velocity. The velocity tells how fast an object is moving and in what direction. Acceleration tells how velocity changes. If the acceleration of an object is known, then the change in velocity can be determined.

Speeding Up  Think about a soccer ball sitting on the ground. If you kick the ball, it starts moving. You exert a force on the ball, and the ball accelerates only while your foot is in contact with the ball. If you look back at all of the examples of objects speeding up, you’ll notice that something is pushing or pulling the object in the direction it is moving, as in Figure 8. The direction of the push or pull is the direction of the force. It also is the direction of the acceleration.
**Slowing Down** If you wanted to slow down an object, you would have to push or pull it against the direction it is moving. An example is given in Figure 9.

Suppose you push a book across a tabletop. When you start pushing, the book speeds up. Sliding friction also acts on the book. After you stop pushing, sliding friction causes the book to slow down and stop.

**Calculating Acceleration** Newton’s second law of motion can be used to calculate acceleration. For example, suppose you pull a 10-kg sled so that the net force on the sled is 5 N. The acceleration can be found as follows:

\[
a = \frac{F_{\text{net}}}{m} = \frac{5 \text{ N}}{10 \text{ kg}} = 0.5 \text{ m/s}^2
\]

The sled keeps accelerating as long as you keep pulling on it. The acceleration does not depend on how fast the sled is moving. It depends only on the net force and the mass of the sled.

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**Applying Math** *Solving a Simple Equation*

**ACCELERATION OF A CAR** A net force of 4,500 N acts on a car with a mass of 1,500 kg. What is the acceleration of the car?

**Solution**

1. **This is what you know:**
   - net force: \( F_{\text{net}} = 4,500 \text{ N} \)
   - mass: \( m = 1,500 \text{ kg} \)

2. **This is what you need to find:** acceleration: \( a = ? \text{ m/s}^2 \)

3. **This is the procedure you need to use:** Substitute the known values for net force and mass into the equation for Newton’s second law of motion to calculate the acceleration:

\[
a = \frac{F_{\text{net}}}{m} = \frac{4,500 \text{ N}}{1,500 \text{ kg}} = 3.0 \frac{\text{N}}{\text{kg}} = 3.0 \text{ m/s}^2
\]

4. **Check your answer:** Multiply your answer by the mass, 1,500 kg. The result should be the given net force, 4,500 N.

**Practice Problems**

1. A book with a mass of 2.0 kg is pushed along a table. If the net force on the book is 1.0 N, what is the book’s acceleration?

2. A baseball has a mass of 0.15 kg. What is the net force on the ball if its acceleration is 40 m/s²?
Turning
Sometimes forces and motion are not in a straight line. If a net force acts at an angle to the direction an object is moving, the object will follow a curved path. The object might be going slower, faster, or at the same speed after it turns. For example, when you shoot a basketball, the ball doesn’t continue to move in a straight line after it leaves your hand. Instead it starts to curve downward, as shown in Figure 10. The force of gravity pulls the ball downward. The ball’s motion is a combination of its original motion and the downward motion due to gravity. This causes the ball to move in a curved path.

Circular Motion
A rider on a merry-go-round ride moves in a circle. This type of motion is called circular motion. If you are in circular motion, your direction of motion is constantly changing. This means you are constantly accelerating. According to Newton’s second law of motion, if you are constantly accelerating, there must be a force acting on you the entire time.

Think about an object on the end of a string whirling in a circle. The force that keeps the object moving in a circle is exerted by the string. The string pulls on the object to keep it moving in a circle. The force exerted by the string is the centripetal force and always points toward the center of the circle. In circular motion the centripetal force is always perpendicular to the motion.

**Figure 10** When the ball is thrown, it doesn’t keep moving in a straight line. Gravity exerts a force downward that makes it move in a curved path. **Infer** how the ball would move if it were thrown horizontally.
**Satellite Motion**  Objects that orbit Earth are satellites of Earth. Satellites go around Earth in nearly circular orbits, with the centripetal force being gravity. Why doesn’t a satellite fall to Earth like a baseball does? Actually, a satellite is falling to Earth just like a baseball.

Suppose Earth were perfectly smooth and you throw a baseball horizontally. Gravity pulls the baseball downward so it travels in a curved path. If the baseball is thrown faster, its path is less curved, and it travels farther before it hits the ground. If the baseball were traveling fast enough, as it fell, its curved path would follow the curve of Earth’s surface as shown in **Figure 11**. Then the baseball would never hit the ground. Instead, it would continue to fall around Earth.

Satellites in orbit are being pulled toward Earth just as baseballs are. The difference is that satellites are moving so fast horizontally that Earth’s surface curves downward at the same rate that the satellites are falling downward. The speed at which a object must move to go into orbit near Earth’s surface is about 8 km/s, or about 29,000 km/h.

To place a satellite into orbit, a rocket carries the satellite to the desired height. Then the rocket fires again to give the satellite the horizontal speed it needs to stay in orbit.

**Air Resistance**

Whether you are walking, running, or biking, air is pushing against you. This push is air resistance. Air resistance is a form of friction that acts to slow down any object moving in the air. Air resistance is a force that gets larger as an object moves faster. Air resistance also depends on the shape of an object. A piece of paper crumpled into a ball falls faster than a flat piece of paper falls.

When an object falls it speeds up as gravity pulls it downward. At the same time, the force of air resistance pushing up on the object is increasing as the object moves faster. Finally, the upward air resistance force becomes large enough to equal the downward force of gravity.

When the air resistance force equals the weight, the net force on the object is zero. By Newton’s second law, the object’s acceleration then is zero, and its speed no longer increases. When air resistance balances the force of gravity, the object falls at a constant speed called the terminal velocity.
**Figure 12** The wrench is spinning as it slides across the table. The center of mass of the wrench, shown by the dots, moves as if the force of friction is acting at that point.

**Center of Mass**

When you throw a stick, the motion of the stick might seem to be complicated. However, there is one point on the stick, called the center of mass, that moves in a smooth path. The center of mass is the point in an object that moves as if all the object’s mass were concentrated at that point. For a symmetrical object, such as a ball, the center of mass is at the object’s center. However, for any object the center of mass moves as if the net force is being applied there.

**Figure 12** shows how the center of mass of a wrench moves as it slides across a table. The net force on the wrench is the force of friction between the wrench and the table. This causes the center of mass to move in a straight line with decreasing speed.

**Summary**

**Force and Acceleration**
- According to Newton’s second law, the net force on an object, its mass, and its acceleration are related by
  \[ F_{\text{net}} = ma \]

**Gravity**
- The force of gravity between any two objects is always attractive and depends on the masses of the objects and the distance between them.

**Using Newton’s Second Law**
- A moving object speeds up if the net force is in the direction of the motion.
- A moving object slows down if the net force is in the direction opposite to the motion.
- A moving object turns if the net force is at an angle to the direction of motion.

**Circular Motion**
- A centripetal force exerted toward the center of the circle keeps an object moving in circular motion.

**Self Check**

1. Make a diagram showing the forces acting on a coasting bike rider traveling at 25 km/h on a flat roadway.
2. Analyze how your weight would change with time if you were on a space ship traveling away from Earth toward the Moon.
3. Explain how the force of air resistance depends on an object’s speed.
4. Infer the direction of the net force acting on a car as it slows down and turns right.
5. Think Critically Three students are pushing on a box. Under what conditions will the motion of the box change?

**Applying Math**

6. Calculate Net Force A car has a mass of 1,500 kg. If the car has an acceleration of 2.0 m/s², what is the net force acting on the car?
7. Calculate Mass During a softball game, a softball is struck by a bat and has an acceleration of 1,500 m/s². If the net force exerted on the softball by the bat is 300 N, what is the softball’s mass?