CHAPTER 4 Forces

Chapter Outline

Each of these basketball players is trying to push the ball. One player is trying to push it into the basket, and the other player is trying to push it away from the basket. If both players push the ball at the same time, where will it go? It depends on which player pushes the ball with greater force. Forces like this come into play in every sport, whether it's kicking a soccer ball, throwing a baseball, or spiking a volleyball. Forces are involved not only in sports such as these but in every motion in our daily lives. In this chapter, you'll see how forces affect the motion of everything from basketballs to planets.

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4.1 What Is Force?

Lesson Objectives

- Define force, and give examples of forces.
- Describe how forces combine and affect motion.

Lesson Vocabulary

- force
- net force
- newton (N)

Introduction

Any time the motion of an object changes, a force has been applied. Force can cause a stationary object to start moving or a moving object to accelerate. The moving object may change its speed, its direction, or both. How much an object's motion changes when a force is applied depends on the strength of the force and the object's mass. You can explore the how force, mass, and acceleration are related by doing the activity at the URL http://www.harcourtschool.com/activity/newton/ . This will provide you with a good hands-on introduction to the concept of force in physics.

Defining Force

Force is defined as a push or a pull acting on an object. Examples of forces include friction and gravity. Both are covered in detail later in this chapter. Another example of force is applied force. It occurs when a person or thing applies force to an object, like the girl pushing the swing in **Figure** 4.1. The force of the push causes the swing to move.

FIGURE 4.1
When this girl pushes the swing away from her, it causes the swing to move in that direction.

Force as a Vector

Force is a vector because it has both size and direction. For example, the girl in **Figure** 4.1 is pushing the swing away from herself. That's the direction of the force. She can give the swing a strong push or a weak push. That's the size, or strength, of the force. Like other vectors, forces can be represented with arrows. **Figure** 4.2 shows some examples. The length of each arrow represents the strength of the force, and the way the arrow points represents the direction of the force. How could you use an arrow to represent the girl's push on the swing in **Figure** 4.1?

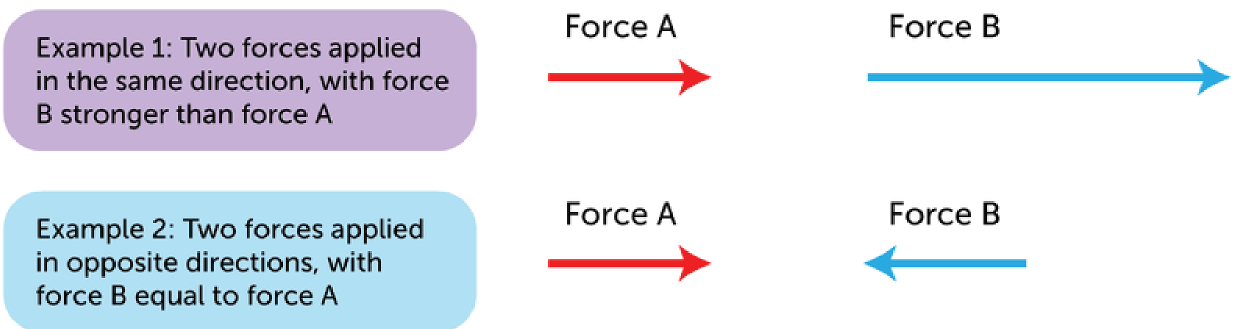


FIGURE 4.2
Forces can vary in both strength and direction.

SI Unit of Force

The SI unit of force is the newton (N). One newton is the amount of force that causes a mass of 1 kilogram to accelerate at 1 m/s^2. Thus, the newton can also be expressed as kg·m/s^2. The newton was named for the scientist Sir Isaac Newton, who is famous for his law of gravity. You'll learn more about Sir Isaac Newton later in the chapter.

Combining Forces

More than one force may act on an object at the same time. In fact, just about all objects on Earth have at least two forces acting on them at all times. One force is gravity, which pulls objects down toward the center of Earth. The other force is an upward force that may be provided by the ground or other surface.

Consider the example in **Figure** 4.3. A book is resting on a table. Gravity pulls the book downward with a force of 20 newtons. At the same time, the table pushes the book upward with a force of 20 newtons. The combined forces acting on the book —or any other object —are called the **net force**. This is the overall force acting on an object that takes into account all of the individual forces acting on the object. You can learn more about the concept of net force at this URL: http://www.mansfieldct.org/schools/mms/staff/hand/lawsunbalancedforce.htm .

Forces Acting in Opposite Directions

When two forces act on an object in opposite directions, like the book on the table, the net force is equal to the difference between the two forces. In other words, one force is subtracted from the other to calculate the net force.

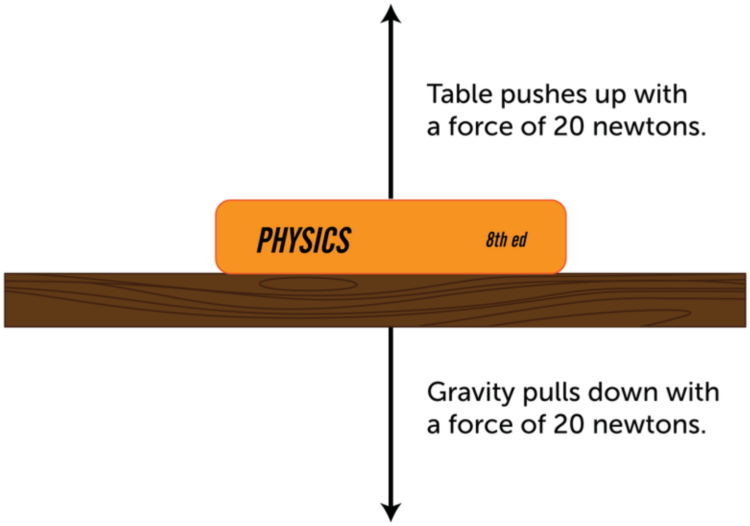


FIGURE 4.3
A book resting on a table is acted on by two opposing forces.

If the opposing forces are equal in strength, the net force is zero. That's what happens with the book on the table. The upward force minus the downward force equals zero (20 N up - 20 N down = 0 N). Because the forces on the book are balanced, the book remains on the table and doesn't move.

In addition to these downward and upward forces, which generally cancel each other out, forces may push or pull an object in other directions. Look at the dogs playing tug-of-war in **Figure** 4.4. One dog is pulling on the rope with a force of 10 newtons to the left. The other dog is pulling on the rope with a force of 12 newtons to the right. These opposing forces are not equal in strength, so they are unbalanced. When opposing forces are unbalanced, the net force is greater than zero. The net force on the rope is 2 newtons to the right, so the rope will move to the right.

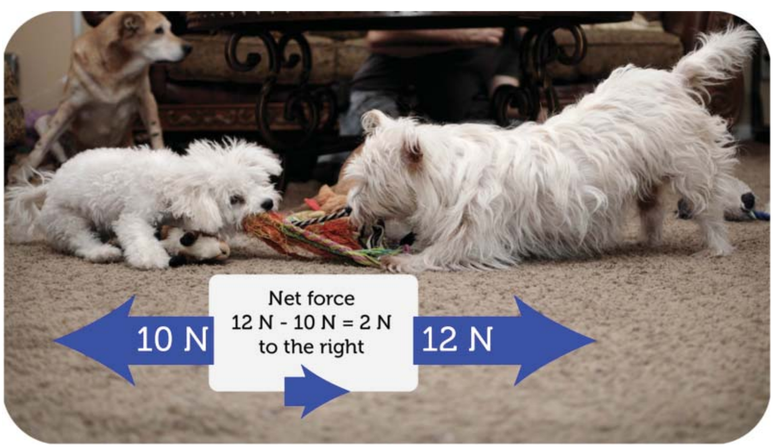


FIGURE 4.4
When unbalanced forces are applied to an object in opposite directions, the smaller force is subtracted from the larger force to yield the net force.

Forces Acting in the Same Direction

Two forces may act on an object in the same direction. You can see an example of this in **Figure** 4.5. After the man on the left lifts up the couch, he will push the couch to the right with a force of 25 newtons. At the same time, the man to the right is pulling the couch to the right with a force of 20 newtons. When two forces act in the same direction, the net force is equal to the sum of the forces. This always results in a stronger force than either of the individual forces alone. In this case, the net force on the couch is 45 newtons to the right, so the couch will move to the right.

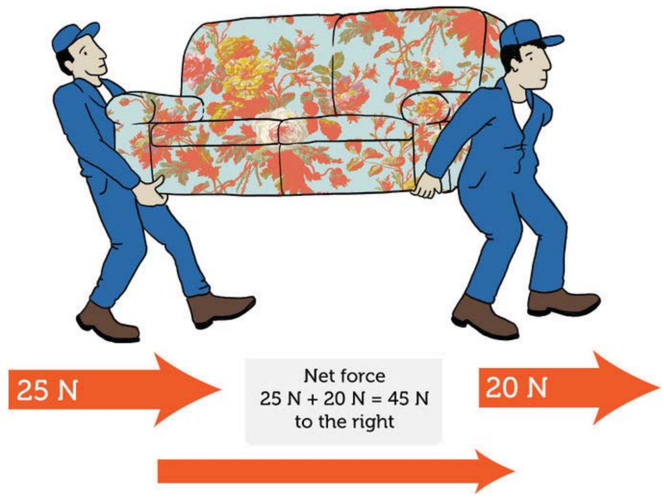
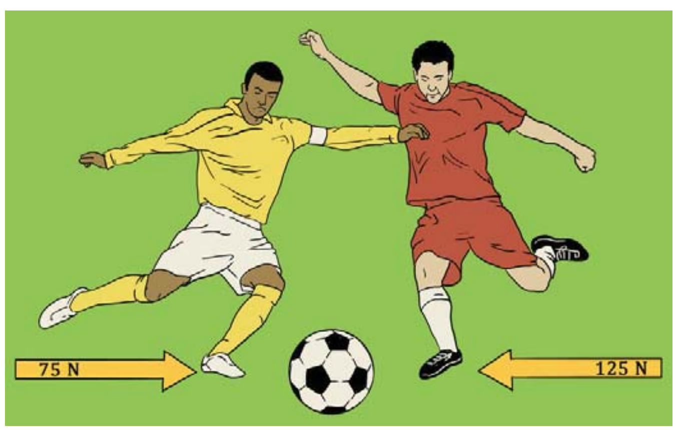


FIGURE 4.5
When two forces are applied to an object in the same direction, the two forces are added to yield the net force.

You Try It!



Problem: The boys in the drawing above are about to kick the soccer ball in opposite directions. What will be the net force on the ball? In which direction will the ball move?

If you need more practice calculating net force, go to this URL: http://www.physicsclassroom.com/class/newtlaws/U2L2d.cfm .

Lesson Summary

- Force is a push or a pull acting on an object. Examples of force include friction and gravity. Force is a vector because it has both size and direction. The SI unit of force is the newton (N).
- The combined forces acting on an object are called the net force. When forces act in opposite directions, they are subtracted to yield the net force. When they act in the same direction, they are added to yield the net force.

Lesson Review Questions

Recall

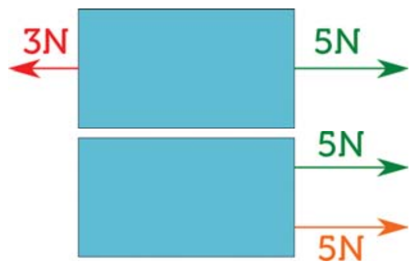
1. Define force. Give an example of a force.
2. What is a newton?
3. What is net force?
4. Describe an example of balanced forces and an example of unbalanced forces.

Apply Concepts

5. What is the net force acting on the block in each diagram below?

a.

b.



Think Critically

6. Explain how forces are related to motion.

Points to Consider

In the next lesson, "Friction," you will read about the force of friction. You experience this force every time you walk. It prevents your feet from slipping out from under you.

- How would you define friction?
- What do you think causes this force?

4.2 Friction

Lesson Objectives

- Describe friction and how it opposes motion.
- Identify types of friction.

Lesson Vocabulary

- fluid
- friction

Introduction

Did you ever rub your hands together to warm them up, like the girl in **Figure** 4.6? Why does this make your hands warmer? The answer is friction.

FIGURE 4.6
This girl is using friction to make her hands warmer.

What Is Friction?

Friction is a force that opposes motion between two surfaces that are touching. Friction can work for or against us. For example, putting sand on an icy sidewalk increases friction so you are less likely to slip. On the other hand, too much friction between moving parts in a car engine can cause the parts to wear out. Other examples of friction are illustrated in **Figure** 4.7. You can see an animation showing how friction opposes motion at this URL: http://www.darvill.clara.net/enforcemot/friction.htm . For a musical introduction to friction from Bill Nye the Science Guy, go to this URL: http://www.youtube.com/watch?v=a5SOCxYft20&feature=related (1:33).

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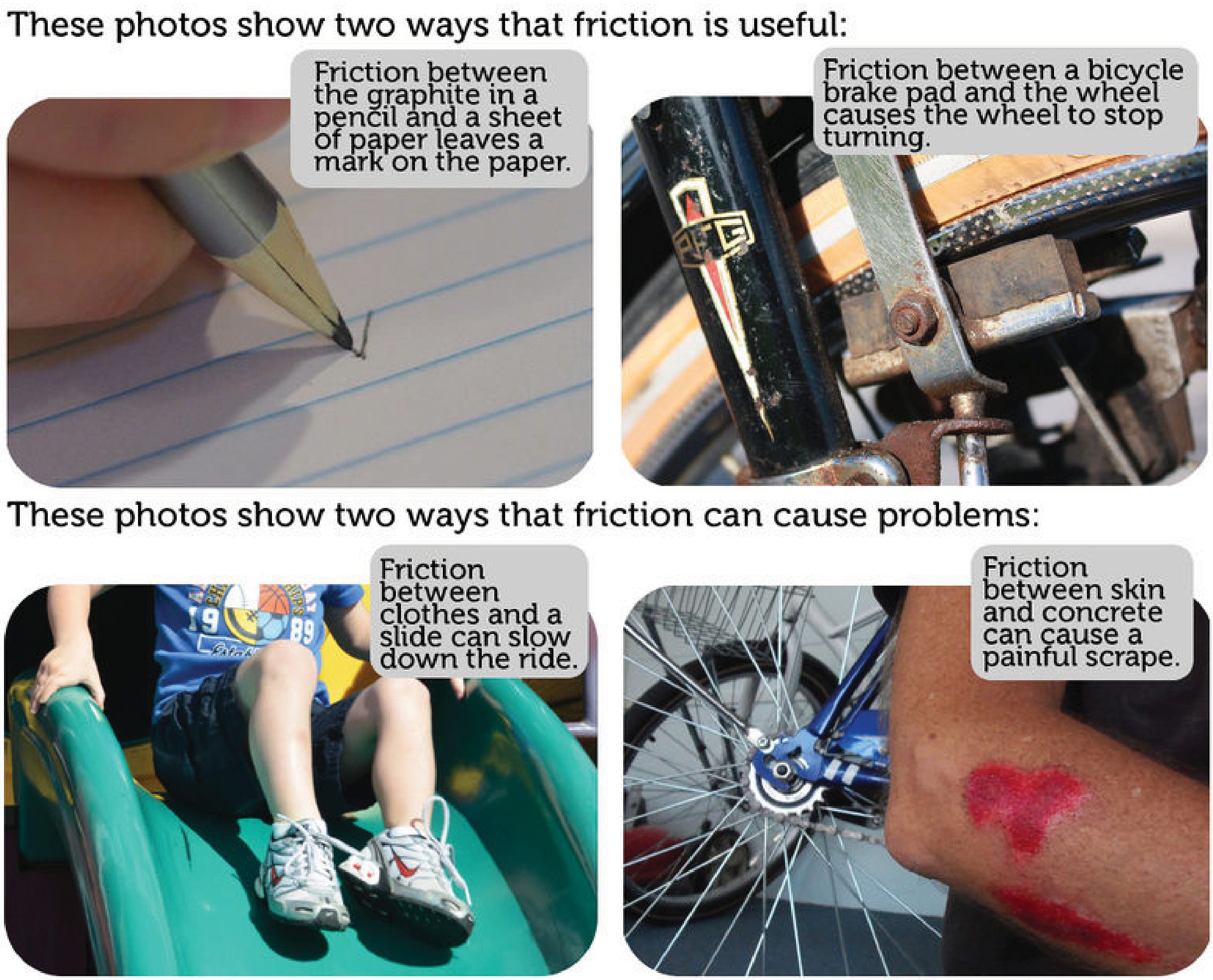

FIGURE 4.7
Sometimes friction is useful. Sometimes it's not.

Why Friction Occurs

Friction occurs because no surface is perfectly smooth. Even surfaces that look smooth to the unaided eye appear rough or bumpy when viewed under a microscope. Look at the metal surfaces in **Figure** 4.8. The metal foil is so smooth that it is shiny. However, when highly magnified, the surface of metal appears to be very bumpy. All those mountains and valleys catch and grab the mountains and valleys of any other surface that contacts the metal. This creates friction.

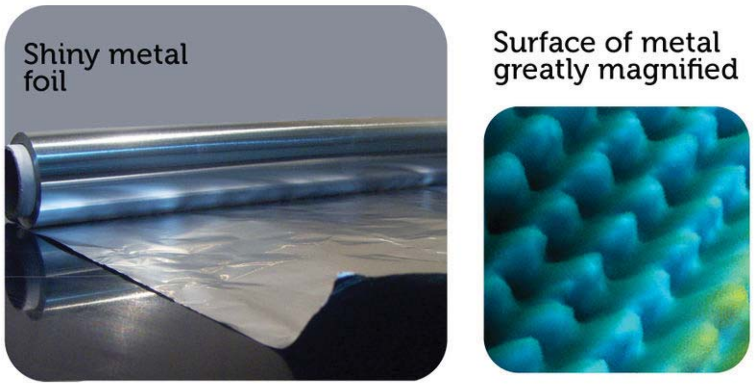

FIGURE 4.8
The surface of metal looks very smooth unless you look at it under a high-powered microscope.

Factors that Affect Friction

Rougher surfaces have more friction between them than smoother surfaces. That's why we put sand on icy sidewalks and roads. Increasing the area of surfaces that are touching also increases the friction between them. That's why you can't slide as far across ice with shoes as you can with skates (see **Figure** 4.9). The greater surface area of shoes causes more friction and slows you down. Heavier objects also have more friction because they press together with greater force. Did you ever try to push boxes or furniture across the floor? It's harder to overcome friction between heavier objects and the floor than it is between lighter objects and the floor.

FIGURE 4.9
The knife-like blades of speed skates minimize friction with the ice.

Friction Produces Heat

You know that friction produces heat. That's why rubbing your hands together makes them warmer. But do you know why the rubbing produces heat? Friction causes the molecules on rubbing surfaces to move faster, so they have more heat energy. Heat from friction can be useful. It not only warms your hands. It also lets you light a match (see **Figure** 4.10). On the other hand, heat from friction can be a problem inside a car engine. It can cause the car to overheat. To reduce friction, oil is added to the engine. Oil coats the surfaces of moving parts and makes them slippery so there is less friction.

FIGURE 4.10
When you rub the surface of a match head across the rough striking surface on the matchbox, the friction produces enough heat to ignite the match.

Types of Friction

There are different ways you could move heavy boxes. You could pick them up and carry them. You could slide them across the floor. Or you could put them on a dolly like the one in **Figure** 4.11 and roll them across the floor. This example illustrates three types of friction: static friction, sliding friction, and rolling friction. Another type of friction is fluid friction. All four types of friction are described below. In each type, friction works opposite the direction of the force applied to a move an object. You can see a video demonstration of the different types of friction at this URL: http://www.youtube.com/watch?v=0bXpYblzkR0&feature=related (1:07).

Static Friction

Static friction acts on objects when they are resting on a surface. For example, if you are walking on a sidewalk, there is static friction between your shoes and the concrete each time you put down your foot (see **Figure** 4.12). Without this static friction, your feet would slip out from under you, making it difficult to walk. Static friction also allows you to sit in a chair without sliding to the floor. Can you think of other examples of static friction?

Sliding Friction

Sliding friction is friction that acts on objects when they are sliding over a surface. Sliding friction is weaker than static friction. That's why it's easier to slide a piece of furniture over the floor after you start it moving than it is to

FIGURE 4.11
A dolly with wheels lets you easily roll boxes across the floor.

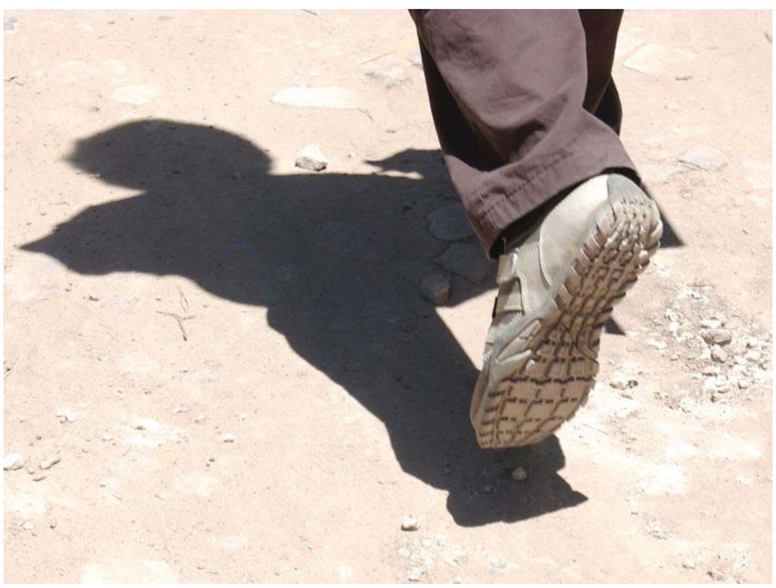

FIGURE 4.12
Static friction between shoes and the sidewalk makes it possible to walk without slipping.

get it moving in the first place. Sliding friction can be useful. For example, you use sliding friction when you write with a pencil and when you put on your bike's brakes.

Rolling Friction

Rolling friction is friction that acts on objects when they are rolling over a surface. Rolling friction is much weaker than sliding friction or static friction. This explains why it is much easier to move boxes on a wheeled dolly than by carrying or sliding them. It also explains why most forms of ground transportation use wheels, including cars, 4-wheelers, bicycles, roller skates, and skateboards. Ball bearings are another use of rolling friction (see **Figure** 4.13). They allow parts of a wheel or other machine to roll rather than slide over one another.

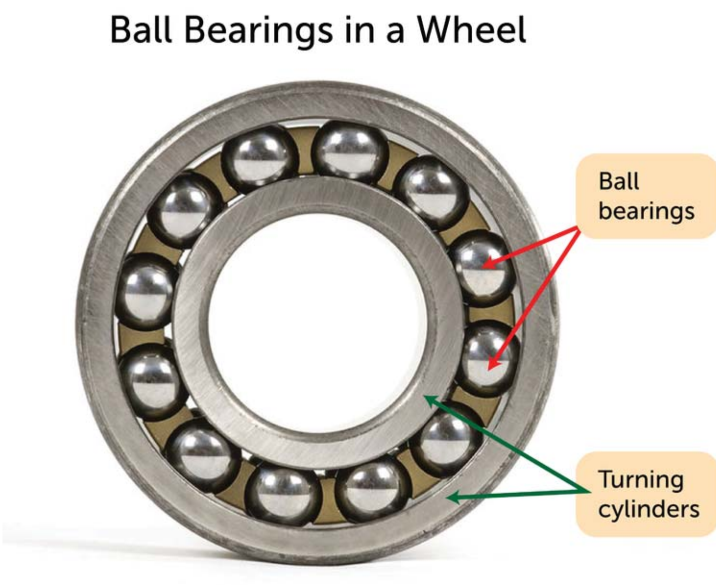

FIGURE 4.13
The ball bearings in this wheel reduce friction between the inner and outer cylinders when they turn.

Fluid Friction

Fluid friction is friction that acts on objects that are moving through a fluid. A **fluid** is a substance that can flow and take the shape of its container. Fluids include liquids and gases. If you've ever tried to push your open hand through the water in a tub or pool, then you've experienced fluid friction between your hand and the water. When a skydiver is falling toward Earth with a parachute, fluid friction between the parachute and the air slows the descent (see **Figure** 4.14). Fluid pressure with the air is called air resistance. The faster or larger a moving object is, the greater is the fluid friction resisting its motion. The very large surface area of a parachute, for example, has greater air resistance than a skydiver's body.

Lesson Summary

- Friction is a force that opposes motion between two surfaces that are touching. Friction occurs because no surface is perfectly smooth. Friction is greater when objects have rougher surfaces, have more surface area that is touching, or are heavier so they press together with greater force.
- Types of friction include static friction, sliding friction, rolling friction, and fluid friction. Fluid friction with air is called air resistance.

Lesson Review Questions

Recall

1. What is friction?
2. List factors that affect friction.
3. How does friction produce heat?

FIGURE 4.14
Fluid friction of the parachute with the air slows this skydiver as he falls.

Apply Concepts

4. Identify two forms of friction that oppose the motion of a moving car.

Think Critically

5. Explain why friction occurs.
6. Compare and contrast the four types of friction described in this lesson.

Points to Consider

A skydiver like the one in **Figure** 4.14 falls to the ground despite the fluid friction of his parachute with the air. Another force pulls him toward Earth. That force is gravity, which is the topic of the next lesson.

- What do you already know about gravity?
- What do you think causes gravity?

4.3 Gravity

Lesson Objectives

- Define gravity.
- State Newton's law of universal gravitation.
- Explain how gravity affects the motion of objects.

Lesson Vocabulary

- gravity
- law of universal gravitation
- orbit
- projectile motion

Introduction

Long, long ago, when the universe was still young, an incredible force caused dust and gas particles to pull together to form the objects in our solar system (see **Figure** 4.15). From the smallest moon to our enormous sun, this force created not only our solar system, but all the solar systems in all the galaxies of the universe. The force is gravity.

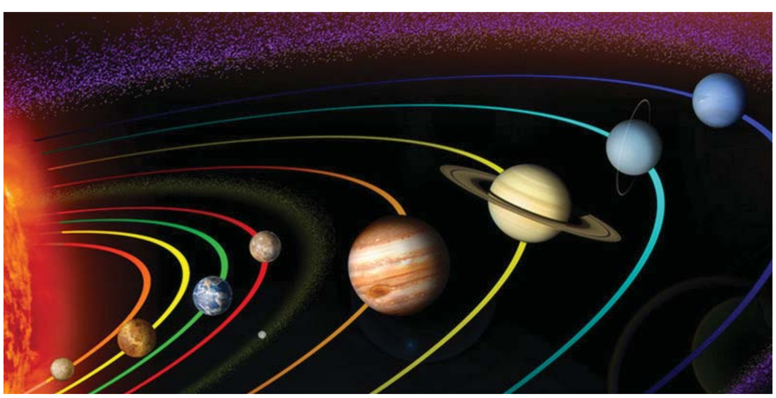

FIGURE 4.15

Gravity helped to form our solar system and all the other solar systems in the universe.

Defining Gravity

Gravity has traditionally been defined as a force of attraction between two masses. According to this conception of gravity, anything that has mass, no matter how small, exerts gravity on other matter. The effect of gravity is that objects exert a pull on other objects. Unlike friction, which acts only between objects that are touching, gravity also acts between objects that are not touching. In fact, gravity can act over very long distances.

Earth's Gravity

You are already very familiar with Earth's gravity. It constantly pulls you toward the center of the planet. It prevents you and everything else on Earth from being flung out into space as the planet spins on its axis. It also pulls objects above the surface, from meteors to skydivers, down to the ground. Gravity between Earth and the moon and between Earth and artificial satellites keeps all these objects circling around Earth. Gravity also keeps Earth moving around the sun.

Gravity and Weight

Weight measures the force of gravity pulling on an object. Because weight measures force, the SI unit for weight is the **newton (N)**. On Earth, a mass of 1 kilogram has a weight of about 10 newtons because of the pull of Earth's gravity On the moon, which has less gravity, the same mass would weigh less. Weight is measured with a scale, like the spring scale in **Figure** 4.16. The scale measures the force with which gravity pulls an object downward.

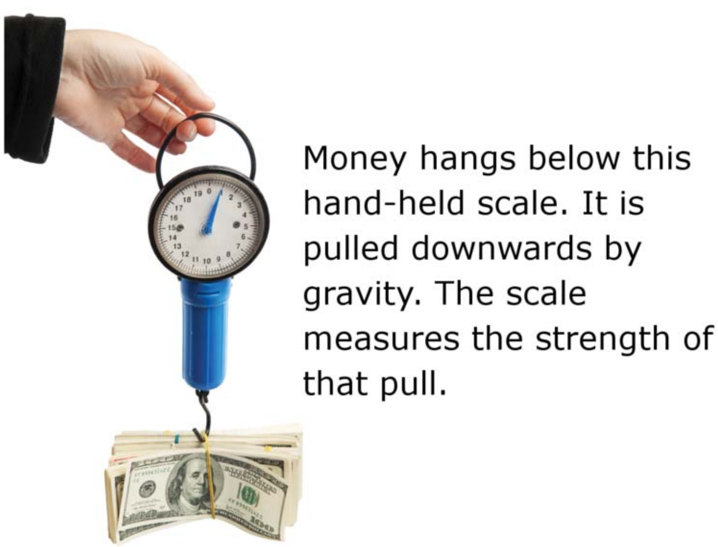

FIGURE 4.16
A scale measures the pull of gravity on an object.

Law of Gravity

People have known about gravity for thousands of years. After all, they constantly experienced gravity in their daily lives. They knew that things always fall toward the ground. However, it wasn't until Sir Isaac Newton developed his law of gravity in the late 1600s that people really began to understand gravity. Newton is pictured in **Figure** 4.17.

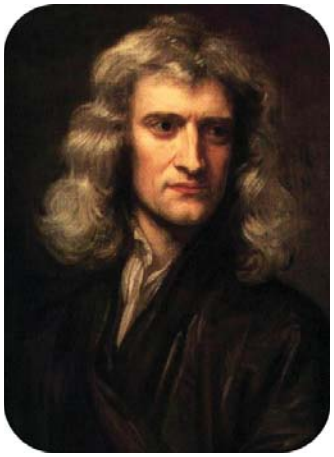

FIGURE 4.17
Sir Isaac Newton discovered that gravity is universal.

Newton's Law of Universal Gravitation

Newton was the first one to suggest that gravity is universal and affects all objects in the universe. That's why his law of gravity is called the **law of universal gravitation**. Universal gravitation means that the force that causes an apple to fall from a tree to the ground is the same force that causes the moon to keep moving around Earth. Universal gravitation also means that while Earth exerts a pull on you, you exert a pull on Earth. In fact, there is gravity between you and every mass around you —your desk, your book, your pen. Even tiny molecules of gas are attracted to one another by the force of gravity.

Newton's law had a huge impact on how people thought about the universe. It explains the motion of objects not only on Earth but in outer space as well. You can learn more about Newton's law of gravity in the video at this URL: http://www.youtube.com/watch?v=O-p8yZYxNGc .

Factors that Influence the Strength of Gravity

Newton's law also states that the strength of gravity between any two objects depends on two factors: the masses of the objects and the distance between them.

- Objects with greater mass have a stronger force of gravity. For example, because Earth is so massive, it attracts you and your desk more strongly than you and your desk attract each other. That's why you and the desk remain in place on the floor rather than moving toward one another.
- Objects that are closer together have a stronger force of gravity. For example, the moon is closer to Earth than it is to the more massive sun, so the force of gravity is greater between the moon and Earth than between the moon and the sun. That's why the moon circles around Earth rather than the sun. This is illustrated in **Figure** 4.18.

You can apply these relationships among mass, distance, and gravity by designing your own roller coaster at this URL: http://www.learner.org/interactives/parkphysics/coaster/ .

Einstein's Theory of Gravity

Newton's idea of gravity can predict the motion of most but not all objects. In the early 1900s, Albert Einstein came up with a theory of gravity that is better at predicting how all objects move. Einstein showed mathematically that gravity is not really a force in the sense that Newton thought. Instead, gravity is a result of the warping, or curving,

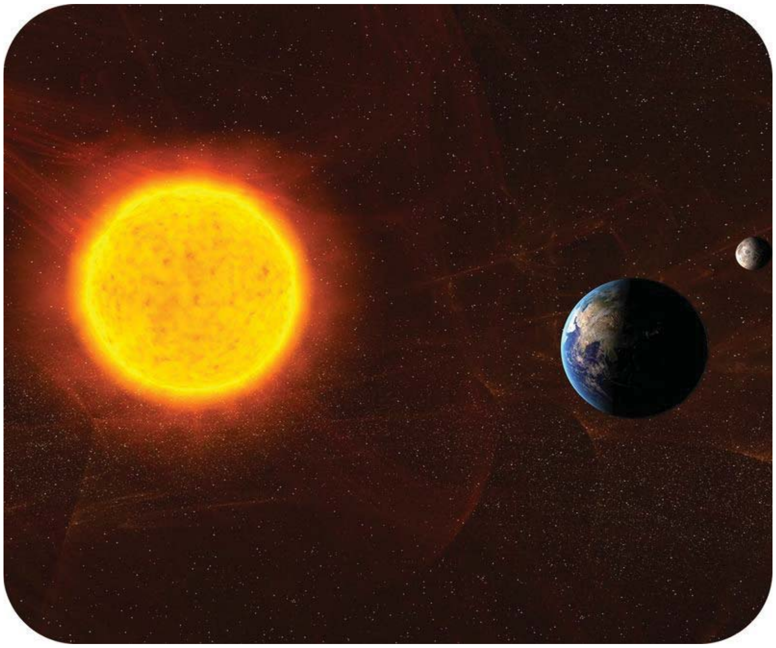

FIGURE 4.18
The moon keeps moving around Earth rather than the sun because it is much closer to Earth.

of space and time. Imagine a bowling ball pressing down on a trampoline. The surface of the trampoline would curve downward instead of being flat. Einstein theorized that Earth and other very massive bodies affect space and time around them in a similar way. This idea is represented in **Figure** 4.19. According to Einstein, objects curve toward one another because of the curves in space and time, not because they are pulling on each other with a force of attraction as Newton thought. You can see an animation of Einstein's theory of gravity at this URL: http://einstein.stanford.edu/Media/Einsteins_Universe_Anima-Flash.html . To learn about recent research that supports Einstein's theory of gravity, go to this URL: http://www.universetoday.com/85401/gravity-probe-b-confirms-two-of-einsteins-space-time-theories/ .

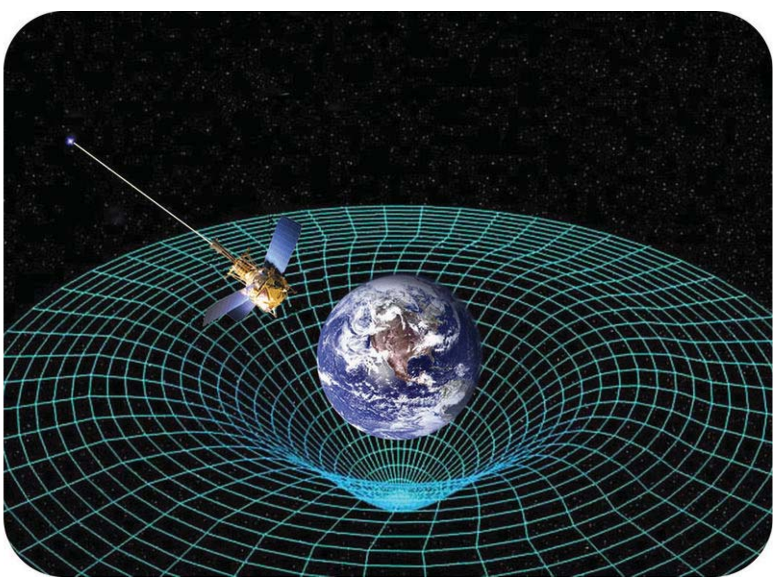

FIGURE 4.19
Einstein thought that gravity is the effect of curves in space and time around massive objects such as Earth. He proposed that the curves in space and time cause nearby objects to follow a curved path. How does this differ from Newton's idea of gravity?

Gravity and Motion

Regardless of what gravity is —a force between masses or the result of curves in space and time —the effects of gravity on motion are well known. You already know that gravity causes objects to fall down to the ground. Gravity affects the motion of objects in other ways as well.

Acceleration Due to Gravity

When gravity pulls objects toward the ground, it causes them to accelerate. Acceleration due to gravity equals 9.8 m/s^2. In other words, the velocity at which an object falls toward Earth increases each second by 9.8 m/s. Therefore, after 1 second, an object is falling at a velocity of 9.8 m/s. After 2 seconds, it is falling at a velocity of 19.6 m/s (9.8 m/s $\times$ 2), and so on. This is illustrated in **Figure** 4.20. You can compare the acceleration due to gravity on Earth, the moon, and Mars with the interactive animation called "Freefall" at this URL: http://jersey.uoregon.edu/vlab/ .

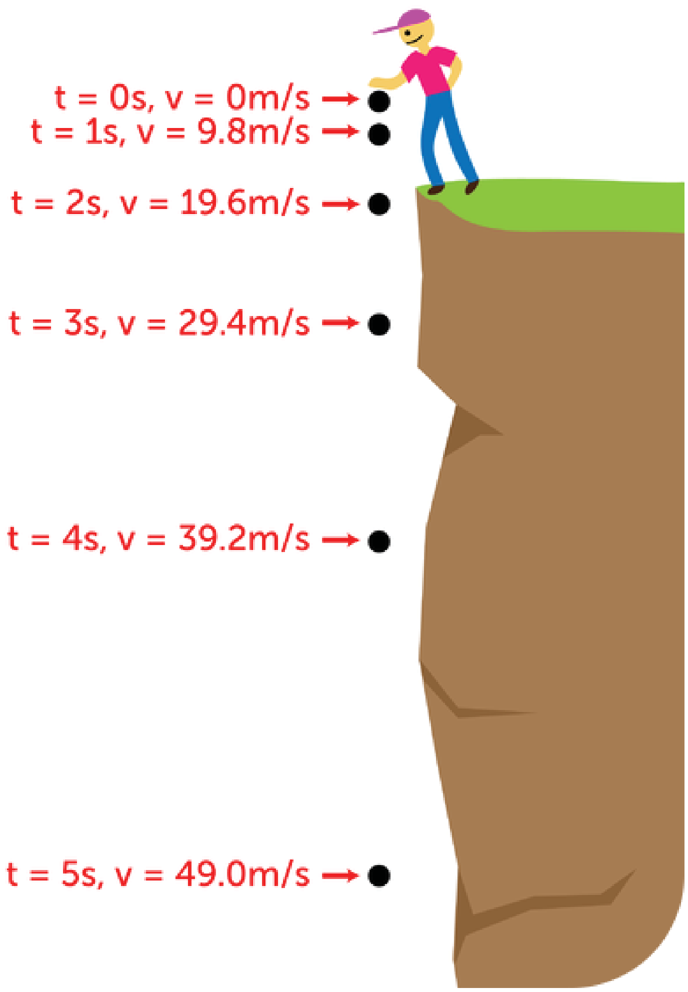

FIGURE 4.20

A boy drops an object at time t = 0 s. At time t = 1 s, the object is falling at a velocity of 9.8 m/s. What is its velocity by time t = 5 ?

You might think that an object with greater mass would accelerate faster than an object with less mass. After all, its greater mass means that it is pulled by a stronger force of gravity. However, a more massive object accelerates at the same rate as a less massive object. The reason? The more massive object is harder to move because of its greater mass. As a result, it ends up moving at the same acceleration as the less massive object.

Consider a bowling ball and a basketball. The bowling ball has greater mass than the basketball. However, if you were to drop both balls at the same time from the same distance above the ground, they would reach the ground together. This is true of all falling objects, unless air resistance affects one object more than another. For example, a falling leaf is slowed down by air resistance more than a falling acorn because of the leaf's greater surface area. However, if the leaf and acorn were to fall in the absence of air (that is, in a vacuum), they would reach the ground at the same time.

Projectile Motion

Earth's gravity also affects the acceleration of objects that start out moving horizontally, or parallel to the ground. Look at **Figure** 4.21. A cannon shoots a cannon ball straight ahead, giving the ball horizontal motion. At the same time, gravity pulls the ball down toward the ground. Both forces acting together cause the ball to move in a curved path. This is called **projectile motion**.

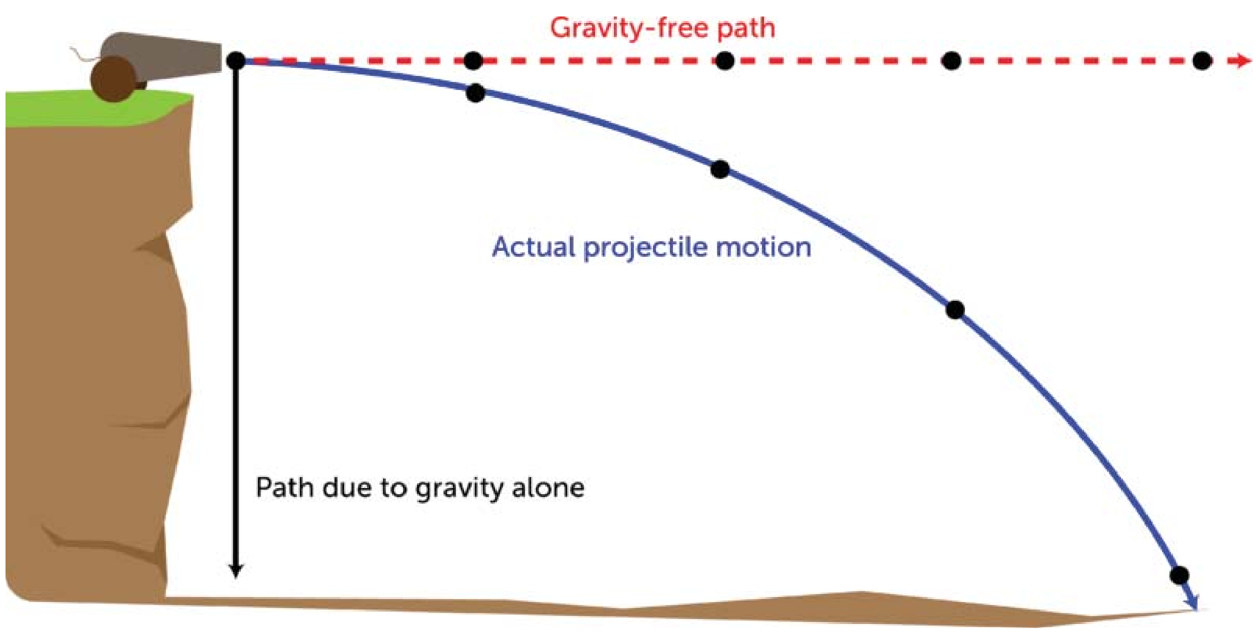

FIGURE 4.21
The cannon ball moves in a curved path because of the combined horizontal and downward forces.

Projectile motion also applies to other moving objects, such as arrows shot from a bow. To hit the bull's eye of a target with an arrow, you actually have to aim for a spot above the bull's eye. That's because by the time the arrow reaches the target, it has started to curve downward toward the ground. **Figure** 4.22 shows what happens if you aim at the bull's eye instead of above it. You can access interactive animations of projectile motion at these URLs:

- http://phet.colorado.edu/en/simulation/projectile-motion
- http://jersey.uoregon.edu/vlab/ *(Select the applet entitled "Cannon.")*

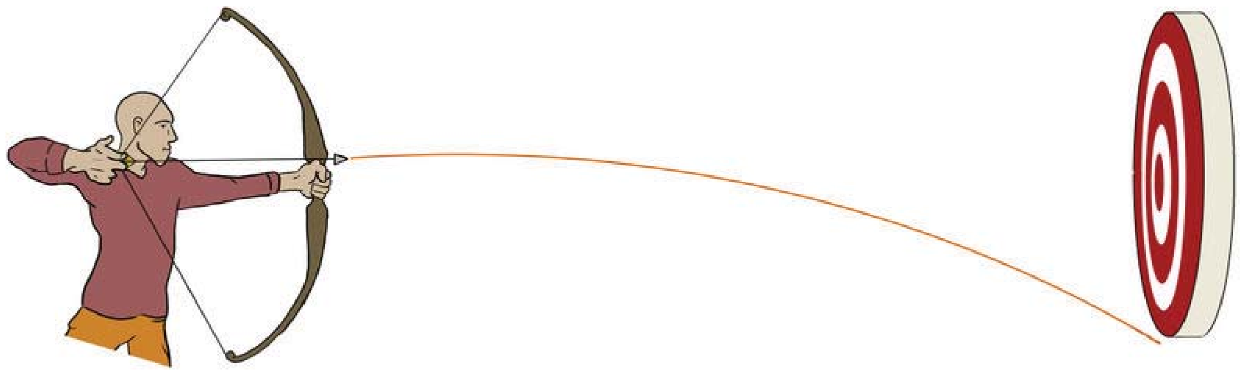

FIGURE 4.22
Aiming at the center of a target is likely to result in a hit below the bull's eye.

Orbital Motion

The moon moves around Earth in a circular path called an **orbit**. Why doesn't Earth's gravity pull the moon down to the ground instead? The moon has enough forward velocity to partly counter the force of Earth's gravity. It constantly falls toward Earth, but it stays far enough away from Earth so that it actually falls around the planet. As a result, the moon keeps orbiting Earth and never crashes into it. The diagram in **Figure** 4.23 shows how this happens. You can explore gravity and orbital motion in depth with the animation at this URL: http://phet.colorado.edu/en/simulation/gravity-and-orbits .

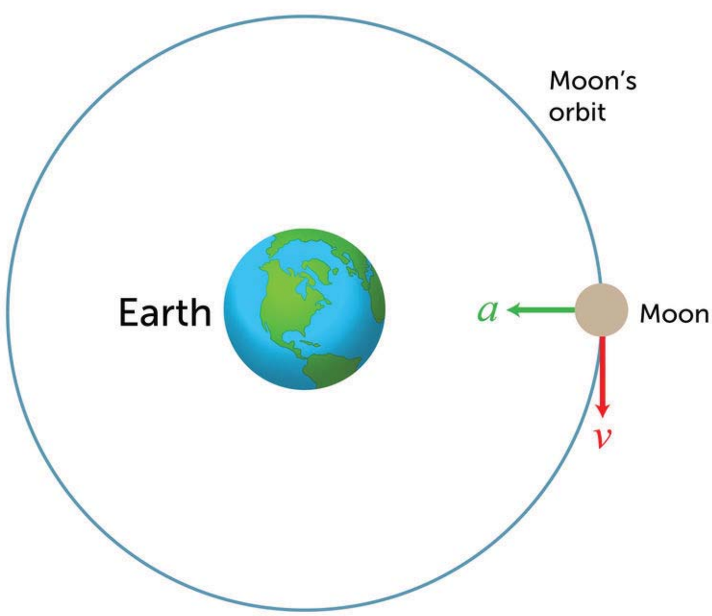

FIGURE 4.23
In this diagram, "v" represents the forward velocity of the moon, and "a" represents the acceleration due to gravity. The line encircling Earth shows the moon's actual orbit, which results from the combination of "v" and "a."

You can see an animated version of this diagram at: http://en.wikipedia.org/wiki/File:Orbital_motion.gif .

Lesson Summary

- Gravity is traditionally defined as a force of attraction between two masses. Weight measures the force of gravity and is expressed in newtons (N).
- According to Newton's law of universal gravitation, gravity is a force of attraction between all objects in the universe, and the strength of gravity depends on the masses of the objects and the distance between them. Einstein's theory of gravity states that gravity is an effect of curves in space and time around massive objects such as Earth.
- Gravity causes falling objects to accelerate at 9.8 m/s^2. Gravity also causes projectile motion and orbital motion.

Lesson Review Questions

Recall

1. What is the traditional definition of gravity?
2. How is weight related to gravity?
3. Summarize Newton's law of universal gravitation.
4. Describe Einstein's idea of gravity.

Apply Concepts

5. Create a poster to illustrate the concept of projectile motion.

Think Critically

6. In the absence of air, why does an object with greater mass fall toward Earth at the same acceleration as an object with less mass?
7. Explain why the moon keeps orbiting Earth.

Points to Consider

The scale you saw in **Figure** 4.16 contains a spring. When an object hangs from the scale, the spring exerts an upward force that partly counters the downward force of gravity. The type of force exerted by a spring is called elastic force, which is the topic of the next lesson.

- Besides springs, what other objects do you think might exert elastic force?
- What other ways might you use elastic force?

4.4 Elastic Force

Lesson Objectives

- Define elasticity and elastic force.
- Describe uses of elastic force.

Lesson Vocabulary

- elastic force
- elasticity

Introduction

The boy in **Figure** 4.24 has a newspaper route. Every morning, he rolls up newspapers for his customers and puts rubber bands around them. The rubber bands keep the newspapers tightly rolled up so it is easy to toss them onto porches and driveways as the boy rides by on his bike. Rubber bands are useful for this purpose because they are elastic.

FIGURE 4.24
A stretchy rubber band holds this newspaper in a tight roll.

Elasticity and Elastic Force

Something that is elastic can return to its original shape after being stretched or compressed. This property is called **elasticity**. As you stretch or compress an elastic material, it resists the change in shape. It exerts a counter force in the opposite direction. This force is called **elastic force**. Elastic force causes the material to spring back to its original shape as soon as the stretching or compressing force is released. You can watch a demonstration of elastic force at this URL: http://www.youtube.com/watch?v=fFtM9JznLh8 (3:57).

MEDIA

Click image to the left for more content.

Using Elastic Force

Elastic force can be very useful. You probably use it yourself every day. A few common uses of elastic force are pictured in **Figure** 4.25. Did you ever use a resistance band like the one in the figure? When you pull on the band, it stretches but doesn't break. The resistance you feel when you pull on it is elastic force. The resistance of the band to stretching is what gives your muscles a workout. After you stop pulling on the band, it returns to its original shape, ready for the next workout.

Springs like the ones in **Figure** 4.26 also have elastic force when they are stretched or compressed. And like stretchy materials, they return to their original shape when the stretching or compressing force is released. Because of these properties, springs are used in scales to measure weight. They also cushion the ride in a car and provide springy support beneath a mattress. Can you think of other uses of springs?

Lesson Summary

- Elasticity is the ability of a material to return to its original shape after being stretched or compressed. Elastic force is the counter force that resists the stretching or compressing of an elastic material.
- Elastic force is very useful. It is used in rubber bands, bungee cords, and bed springs, to name just a few uses.

Lesson Review Questions

Recall

1. What is elasticity?
2. Describe elastic force.
3. Identify uses of elastic force.

FIGURE 4.25
All these items are useful because they can be stretched and then return to their original shape.

FIGURE 4.26
Springs are useful because they return to their original shape after being stretched or compressed.

Apply Concepts

4. Think of a way you could demonstrate elastic force to a younger student. Describe the procedure you would follow and the materials you would use.

Think Critically

5. Explain how springs are used in scales to measure weight.

Points to Consider

In this chapter, you read about Newton's law of universal gravitation. Newton developed several other laws as well. In the next chapter, "Newton's Laws of Motion," you'll read about his three laws of motion. Recall what you already know about motion.

- What is motion? What are examples of motion?
- What causes changes in motion? What are changes in motion called?

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CHAPTER 5 Newton's Laws of Motion

Chapter Outline

The sprinter in this photo is pushing off from the blocks at the start of a race. The blocks provide a counter force so she can take off in a hurry. With great effort, she will go from motionless to top speed in just a few seconds. She won't slow down until she crosses the finish line. By then, she will be going so fast that it will take her almost as much time to come to a full stop as it did to run the race.

No doubt you've experienced motions like these, even if you've never run a race. But do you know what explains these motions? For example, do you know why it's as hard to stop running as it is to start? These and other aspects of motion are explained by three laws of motion. The laws were developed by Sir Isaac Newton in the late 1600s. You'll learn about Newton's laws of motion in this chapter and how and why objects move as they do.

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5.1 Newton's First Law

Lesson Objectives

- State Newton's first law of motion.
- Define inertia, and explain its relationship to mass.

Lesson Vocabulary

- inertia
- Newton's first law of motion

Introduction

The amusement park ride pictured in **Figure** 5.1 keeps changing direction as it zooms back and forth. Each time it abruptly switches direction, the riders are forced to the opposite side of the car. What force causes this to happen? In this lesson, you'll find out.

FIGURE 5.1
Amusement park rides like this one are exciting because of the strong forces the riders feel.

Force and Motion

Newton's first law of motion states that an object's motion will not change unless an unbalanced force acts on the object. If the object is at rest, it will stay at rest. If the object is in motion, it will stay in motion and its velocity will remain the same. In other words, neither the direction nor the speed of the object will change as long as the net force acting on it is zero. You can watch a video about Newton's first law at this URL: http://videos.howstuffworks.com/discovery/29382-assignment-discovery-newtons-first-law-video.htm .

Look at the pool balls in **Figure** 5.2. When a pool player pushes the pool stick against the white ball, the white ball is set into motion. Once the white ball is rolling, it rolls all the way across the table and stops moving only after it crashes into the cluster of colored balls. Then, the force of the collision starts the colored balls moving. Some may roll until they bounce off the raised sides of the table. Some may fall down into the holes at the edges of the table. None of these motions will occur, however, unless that initial push of the pool stick is applied. As long as the net force on the balls is zero, they will remain at rest.

FIGURE 5.2
Pool balls remain at rest until an unbalanced force is applied to them. After they are in motion, they stay in motion until another force opposes their motion.

Inertia

Newton's first law of motion is also called the law of inertia. **Inertia** is the tendency of an object to resist a change in its motion. If an object is already at rest, inertia will keep it at rest. If the object is already moving, inertia will keep it moving.

Think about what happens when you are riding in a car that stops suddenly. Your body moves forward on the seat. Why? The brakes stop the car but not your body, so your body keeps moving forward because of inertia. That's why it's important to always wear a seat belt. Inertia also explains the amusement park ride in **Figure** 5.1. The car keeps changing direction, but the riders keep moving in the same direction as before. They slide to the opposite side of the car as a result. You can see an animation of inertia at this URL: http://www.physicsclassroom.com/mmedia/newtlaws/cci.cfm .

Inertia and Mass

The inertia of an object depends on its mass. Objects with greater mass also have greater inertia. Think how hard it would be to push a big box full of books, like the one in **Figure** 5.3. Then think how easy it would be to push the box if it was empty. The full box is harder to move because it has greater mass and therefore greater inertia.

FIGURE 5.3
The tendency of an object to resist a change in its motion depends on its mass. Which box has greater inertia?

Overcoming Inertia

To change the motion of an object, inertia must be overcome by an unbalanced force acting on the object. Until the soccer player kicks the ball in **Figure** 5.4, the ball remains motionless on the ground. However, when the ball is kicked, the force on it is suddenly unbalanced. The ball starts moving across the field because its inertia has been overcome.

FIGURE 5.4
Force must be applied to overcome the inertia of a soccer ball at rest.

Once objects start moving, inertia keeps them moving without any additional force being applied. In fact, they won't stop moving unless another unbalanced force opposes their motion. What if the rolling soccer ball is not kicked by another player or stopped by a fence or other object? Will it just keep rolling forever? It would if another unbalanced force did not oppose its motion. Friction —in this case rolling friction with the ground —will oppose the motion of the rolling soccer ball. As a result, the ball will eventually come to rest. Friction opposes the motion of all moving objects, so, like the soccer ball, all moving objects eventually come to a stop even if no other forces oppose their motion.

Lesson Summary

- Newton's first law of motion states that an object's motion will not change unless an unbalanced force acts on the object. If the object is at rest, it will stay at rest. If the object is in motion, it will stay in motion.
- Inertia is the tendency of an object to resist a change in its motion. The inertia of an object depends on its mass. Objects with greater mass have greater inertia. To overcome inertia, an unbalanced force must be applied to an object.

Lesson Review Questions

Recall

1. State Newton's first law of motion.
2. Define inertia.
3. How does an object's mass affect its inertia?

Apply Concepts

4. Assume you are riding a skateboard and you run into a curb. Your skateboard suddenly stops its forward motion. Apply the concept of inertia to this scenario, and explain what happens next.

Think Critically

5. Why is Newton's first law of motion also called the law of inertia?

Points to Consider

In this lesson, you read that the mass of an object determines its inertia. You also learned that an unbalanced force must be applied to an object to overcome its inertia, whether it is moving or at rest. An unbalanced force causes an object to accelerate.

- Predict how the mass of an object affects its acceleration when an unbalanced force is applied to it.
- How do you think the acceleration of an object is related to the strength of the unbalanced force acting on it?

5.2 Newton's Second Law

Lesson Objectives

- State Newton's second law of motion.
- Identify the relationship between acceleration and weight.

Lesson Vocabulary

- Newton's second law of motion

Introduction

A car's gas pedal, like the one in **Figure** 5.5, is sometimes called the accelerator. That's because it controls the acceleration of the car. Pressing down on the gas pedal gives the car more gas and causes the car to speed up. Letting up on the gas pedal gives the car less gas and causes the car to slow down. Whenever an object speeds up, slows down, or changes direction, it accelerates. Acceleration is a measure of the change in velocity of a moving object. Acceleration occurs whenever an object is acted upon by an unbalanced force.

FIGURE 5.5
The car pedal on the right controls the amount of gas the engine gets. How does this affect the car's acceleration?

Acceleration, Force, and Mass

Newton determined that two factors affect the acceleration of an object: the net force acting on the object and the object's mass. The relationships between these two factors and motion make up **Newton's second law of motion**. This law states that the acceleration of an object equals the net force acting on the object divided by the object's mass. This can be represented by the equation:

$$\text{Acceleration} = \frac{\text{Net force}}{\text{Mass}}, \text{ or}$$
$$a = \frac{F}{m}$$

You can watch a video about how Newton's second law of motion applies to football at this URL: http://science360.gov/obj/video/58e62534-e38d-430b-bfb1-c505e628a2d4 .

Direct and Inverse Relationships

Newton's second law shows that there is a direct relationship between force and acceleration. The greater the force that is applied to an object of a given mass, the more the object will accelerate. For example, doubling the force on the object doubles its acceleration. The relationship between mass and acceleration, on the other hand, is an inverse relationship. The greater the mass of an object, the less it will accelerate when a given force is applied. For example, doubling the mass of an object results in only half as much acceleration for the same amount of force.

Consider the example of a batter, like the boy in **Figure** 5.6. The harder he hits the ball, the greater will be its acceleration. It will travel faster and farther if he hits it with more force. What if the batter hits a baseball and a softball with the same amount of force? The softball will accelerate less than the baseball because the softball has greater mass. As a result, it won't travel as fast or as far as the baseball.

FIGURE 5.6

Hitting a baseball with greater force gives it greater acceleration. Hitting a softball with the same amount of force results in less acceleration. Can you explain why?

Calculating Acceleration

The equation for acceleration given above can be used to calculate the acceleration of an object that is acted on by an unbalanced force. For example, assume you are pushing a large wooden trunk, like the one shown in **Figure** 5.7. The trunk has a mass of 10 kilograms, and you are pushing it with a force of 20 newtons. To calculate the acceleration of the trunk, substitute these values in the equation for acceleration:

$$a = \frac{F}{m} = \frac{20 \text{ N}}{10 \text{ kg}} = \frac{2 \text{ N}}{\text{kg}}$$

Recall that one newton (1 N) is the force needed to cause a 1-kilogram mass to accelerate at 1 m/s^2. Therefore, force can also be expressed in the unit $\text{kg}\cdot\text{m/s}^2$. This way of expressing force can be substituted for newtons in the solution to the problem:

$$a = \frac{2 \text{ N}}{\text{kg}} = \frac{2 \text{ kg}\cdot\text{m/s}^2}{\text{kg}} = 2 \text{ m/s}^2$$

Why are there no kilograms in the final answer to this problem? The kilogram units in the numerator and denominator of the fraction cancel out. As a result, the answer is expressed in the correct units for acceleration: m/s^2.

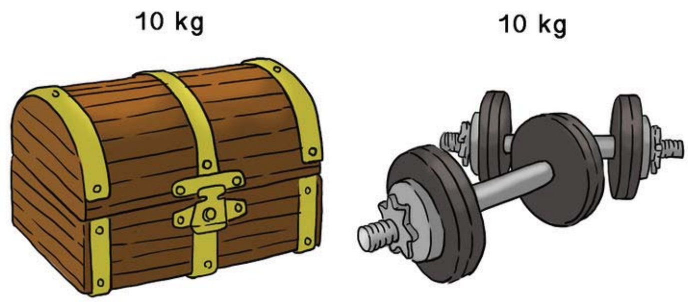

FIGURE 5.7
This empty trunk has a mass of 10 kilograms. The weights also have a mass of 10 kilograms. If the weights are placed in the trunk, what will be its mass? How will this affect its acceleration?

You Try It!

Problem: Assume that you add the weights to the trunk in **Figure** 5.7. If you push the trunk and weights with a force of 20 N, what will be the trunk's acceleration?

Need more practice? You can find additional problems at this URL: http://www.auburnschools.org/ajhs/lmcrowe/Week%2014/WorksheetPracticeProblemsforNewtons2law.pdf .

Acceleration and Weight

Newton's second law of motion explains the weight of objects. Weight is a measure of the force of gravity pulling on an object of a given mass. It's the force (F) in the acceleration equation that was introduced above:

$$a = \frac{F}{m}$$

This equation can also be written as:

$$F = m \times a$$

The acceleration due to gravity of an object equals 9.8 m/s^2, so if you know the mass of an object, you can calculate its weight as:

$$F = m \times 9.8 \text{ m/s}^2$$

As this equation shows, weight is directly related to mass. As an object's mass increases, so does its weight. For example, if mass doubles, weight doubles as well. You can learn more about weight and acceleration at this URL: http://www.nasa.gov/mov/192448main_018_force_equals_mass_time.mov .

Problem Solving

Problem: Daisy has a mass of 35 kilograms. How much does she weigh?

Solution: Use the formula: $F = m \times 9.8 \text{ m/s}^2$.

$F = 35 \text{ kg} \times 9.8 \text{ m/s}^2 = 343.0 \text{ kg} \cdot \text{m/s}^2 = 343.0 \text{ N}$

You Try It!

Problem: Daisy's dad has a mass is 70 kg, which is twice Daisy's mass. Predict how much Daisy's dad weighs. Then calculate his weight to see if your prediction is correct.

Helpful Hints

The equation for calculating weight ($F = m \times a$) works only when the correct units of measurement are used.

- Mass must be in kilograms (kg).
- Acceleration must be in m/s^2.
- Weight (F) is expressed in kg·m/s^2 or in newtons (N).

Lesson Summary

- Newton's second law of motion states that the acceleration of an object equals the net force acting on the object divided by the object's mass.
- Weight is a measure of the force of gravity pulling on an object of a given mass. It equals the mass of the object (in kilograms) times the acceleration due to gravity (9.8 m/s^2).

Lesson Review Questions

Recall

1. State Newton's second law of motion.
2. Describe how the net force acting on an object is related to its acceleration.
3. If the mass of an object increases, how is its acceleration affected, assuming the net force acting on the object remains the same?
4. What is weight?

Apply Concepts

5. Tori applies a force of 20 newtons to move a bookcase with a mass of 40 kg. What is the acceleration of the bookcase?
6. Ollie has a mass of 45 kilograms. What is his weight in newtons?

Think Critically

7. If you know your weight in newtons, how could you calculate your mass in kilograms? What formula would you use?

Points to Consider

Assume that a 5-kilogram skateboard and a 50-kilogram go-cart start rolling down a hill. Both are moving at the same speed. You and a friend want to stop before they plunge into a pond at the bottom of the hill.

- Which will be harder to stop: the skateboard or the go-cart?
- Can you explain why?

5.3 Newton's Third Law

Lesson Objectives

- State Newton's third law of motion.
- Describe momentum and the conservation of momentum.

Lesson Vocabulary

- law of conservation of momentum
- momentum
- Newton's third law of motion

Introduction

Look at the skateboarders in **Figure** 5.8. When they push against each other, it causes them to move apart. The harder they push together, the farther apart they move. This is an example of Newton's third law of motion.

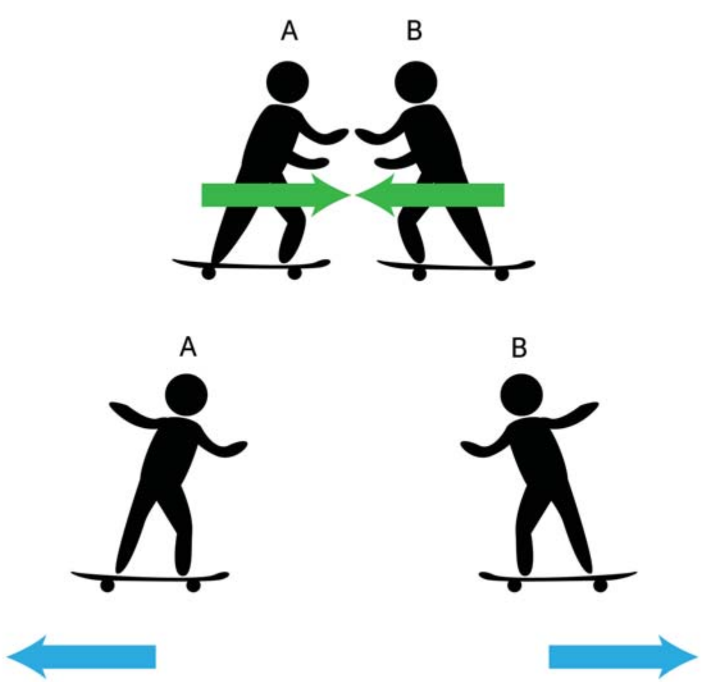

FIGURE 5.8
A and B move apart by first pushing together.

Action and Reaction

Newton's third law of motion states that every action has an equal and opposite reaction. This means that forces always act in pairs. First an action occurs, such as the skateboarders pushing together. Then a reaction occurs that is equal in strength to the action but in the opposite direction. In the case of the skateboarders, they move apart, and the distance they move depends on how hard they first pushed together. You can see other examples of actions and reactions in **Figure** 5.9. You can watch a video about actions and reactions at this URL: http://www.nasa.gov/mov/192449main_019_law_of_action.mov .

FIGURE 5.9

Each example shown here includes an action and reaction.

You might think that actions and reactions would cancel each other out like balanced forces do. Balanced forces, which are also equal and opposite, cancel each other out because they act on the same object. Action and reaction forces, in contrast, act on different objects, so they don't cancel each other out and, in fact, often result in motion. For example, in **Figure** 5.9, the kangaroo's action acts on the ground, but the ground's reaction acts on the kangaroo. As a result, the kangaroo jumps away from the ground. One of the action-reaction examples in the figure above does not result in motion. Do you know which one it is?

Momentum

What if a friend asked you to play catch with a bowling ball, like the one pictured in **Figure** 5.10? Hopefully, you would refuse to play! A bowling ball would be too heavy to catch without risk of injury —assuming you could even throw it. That's because a bowling ball has a lot of mass. This gives it a great deal of momentum. **Momentum** is a property of a moving object that makes the object hard to stop. It equals the object's mass times its velocity. It can be represented by the equation:

$$\text{Momentum} = \text{Mass} \times \text{Velocity}$$

This equation shows that momentum is directly related to both mass and velocity. An object has greater momentum if it has greater mass, greater velocity, or both. For example, a bowling ball has greater momentum than a softball when both are moving at the same velocity because the bowling ball has greater mass. However, a softball moving at a very high velocity —say, 100 miles an hour —would have greater momentum than a slow-rolling bowling ball. If an object isn't moving at all, it has no momentum. That's because its velocity is zero, and zero times anything is zero.

FIGURE 5.10
A bowling ball and a softball differ in mass. How does this affect their momentum?

Calculating Momentum

Momentum can be calculated by multiplying an object's mass in kilograms (kg) by its velocity in meters per second (m/s). For example, assume that a golf ball has a mass of 0.05 kg. If the ball is traveling at a velocity of 50 m/s, its momentum is:

$$\text{Momentum} = 0.05 \text{ kg} \times 50 \text{ m/s} = 2.5 \text{ kg} \cdot \text{m/s}$$

Note that the SI unit for momentum is kg·m/s.

Problem Solving

Problem: What is the momentum of a 40-kg child who is running straight ahead with a velocity of 2 m/s?

Solution: The child has momentum of: 40 kg $\times$ 2 m/s = 80 kg·m/s.

You Try It!

Problem: Which football player has greater momentum?

Player A: mass = 60 kg; velocity = 2.5 m/s

Player B: mass = 65 kg; velocity = 2.0 m/s

Conservation of Momentum

When an action and reaction occur, momentum is transferred from one object to the other. However, the combined momentum of the objects remains the same. In other words, momentum is conserved. This is the **law of conservation of momentum**.

Consider the example of a truck colliding with a car, which is illustrated in **Figure** 5.11. Both vehicles are moving in the same direction before and after the collision, but the truck is moving faster than the car before the collision occurs. During the collision, the truck transfers some of its momentum to the car. After the collision, the truck is moving slower and the car is moving faster than before the collision occurred. Nonetheless, their combined momentum is the same both before and after the collision. You can see an animation showing how momentum is conserved in a head-on collision at this URL: http://www.physicsclassroom.com/mmedia/momentum/cthoi.cfm .

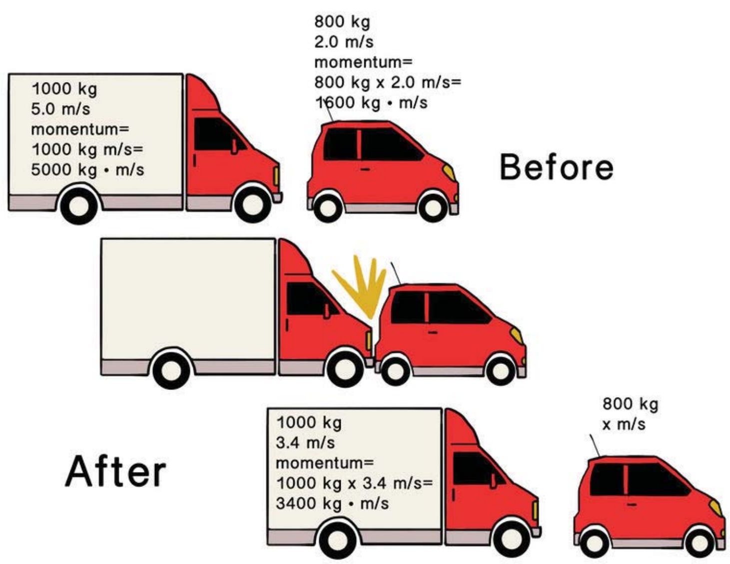

FIGURE 5.11
How can you tell momentum has been conserved in this collision?

Lesson Summary

- Newton's third law of motion states that every action has an equal and opposite reaction.
- Momentum is a property of a moving object that makes it hard to stop. It equals the object's mass times its velocity. When an action and reaction occur, momentum may be transferred from one object to another, but their combined momentum remains the same. This is the law of conservation of momentum.

Lesson Review Questions

Recall

1. State Newton's third law of motion.
2. Define momentum.

3. If you double the velocity of a moving object, how is its momentum affected?

Apply Concepts

4. A large rock has a mass of 50 kg and is rolling downhill at 3 m/s. What is its momentum?
5. Create a diagram to illustrate the transfer and conservation of momentum when a moving object collides with a stationary object.

Think Critically

6. The reaction to an action is an equal and opposite force. Why doesn't this yield a net force of zero?
7. Momentum is a property of an object, but it is different than a physical or chemical property, such as boiling point or flammability. How is momentum different?

Points to Consider

In this chapter, you learned about forces and motions of solid objects, such as balls and cars. In the next chapter, "Fluid Forces," you will learn about forces in fluids, which include liquids and gases.

- How do fluids differ from solids?
- What might be examples of forces in fluids? For example, what force allows some objects to float in water?

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