5.3 Forces and Equilibrium

We almost never feel only one force. For example, friction and weight are two forces that both act on us when we're walking. It is the total of *all* forces acting on our bodies that determines how we move. This section is about how forces can be added and subtracted.

VOCABULARY

net force - the sum of all forces acting on an object.

balanced forces - combined forces that result in a zero net force on an object.

Adding forces

An example The sum of all the forces acting on an object is called the **net force**. The word *net* means "total." *Net force* also means that the direction of each force is considered when multiple forces are added. Consider a flying airplane (Figure 5.15). Four forces act on the plane: weight, drag (air friction), the thrust of the engines, and the lift force caused by the flow of air over the wings. For a plane to fly at a constant speed on a level path, the forces must all balance. **Balanced forces** result in a net force of zero.

A pilot must always be aware of these four forces and know how to change them in order to speed up, slow down, lift off, and land. For example, to speed up there must be a net force in the forward direction. The thrust must be greater than the drag. To climb, there must be an upward net force. The lift force must be greater than the weight.

Figure 5.15: *Four forces act on a plane as it flies.*

Adding *x-y* components To calculate the net force on an object, you must add the forces in each direction separately. Remember to define positive and negative directions for both the x-direction and y-direction. In the diagram above, $+x$ is to the right and $+y$ is up. The net force in the x-direction is zero because the +20,000 N and −20,000 N add up to zero. The net force in the y-direction is +5,000 N (+55,000 N − 50,000 N). The plane climbs because there is a positive (upward) net force.

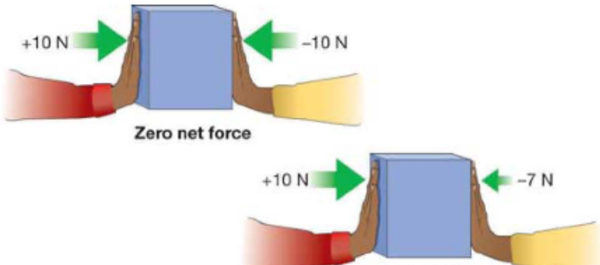
Equilibrium

Net force can be zero or not zero

When many forces act on the same object either:

The net force is zero, or

The net force is NOT zero.



Definition of equilibrium

When the net force on an object is zero, we say the object is in **equilibrium**. Equilibrium does NOT mean there are no forces! Equilibrium means all forces cancel each other out leaving zero net force. For example, when the net force is zero, an object at rest will stay at rest. Interestingly, an object can be in motion at constant speed and still be in equilibrium. This happens when a pushing force and a friction force are equal but opposite in direction so the object does not speed up or slow down (Figure 5.16).

Using equilibrium to find unknown forces

The idea of equilibrium is often used in reverse. Instead of thinking "an object in equilibrium stays at rest," we think "an object at rest must be in equilibrium." If an object is at rest, *the net force on it must be zero*. This fact often allows us to find the strength and direction of forces that must be there even if we don't directly cause them.

When net force is not zero

If the net force is NOT zero, then the motion of an object will change. An object at rest will start moving. An object that is moving may change its velocity. In other words, unbalanced forces cause *acceleration*.

VOCABULARY

equilibrium - the state in which the net force on an object is zero.

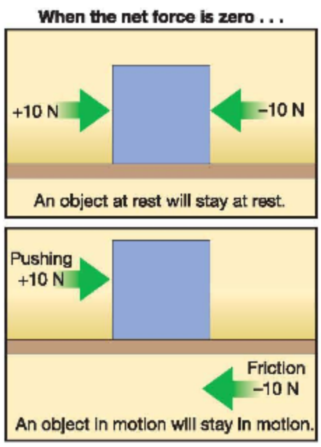


Figure 5.16: *Objects are in equilibrium when the net force is zero.*

Normal forces

Definition of normal force Imagine a book sitting on a table (Figure 5.17). Gravity pulls the book downward with the force of the book's weight. The book is at rest, so the net force must be zero. But what force balances the weight? The table exerts an upward force on the book called the **normal force**. The word *normal* here has a different meaning from what you might expect. In mathematics, *normal* means "perpendicular." The force that the table exerts is perpendicular to the table's surface. The normal force is also sometimes called the *support force*.

When normal force is created A normal force is created whenever an object is in contact with a surface. The normal force has *equal strength* to the force pressing the object into the surface, which is often the object's weight. The normal force has *opposite direction* to the force pressing the object into the surface. For example, the weight of a book presses down on the table's surface. The normal force is equal in strength to the book's weight but acts upward on the book, in the opposite direction from the weight.

What normal force acts on The normal force acts on the object pressing into the surface. That means, in this example, the normal force *acts on the book*. The normal force is created by the book *acting on the table*.

Strength of the normal force What happens to the normal force if you put a brick on top of the book? The brick makes the book press harder into the table. The book does not move, so the normal force must be the same strength as the total weight of the book and the brick (Figure 5.18). The normal force acting on the book increases to keep the book in balance.

How the normal force is created How does a table "know" how much normal force to supply? The answer is that normal force is very similar to the force exerted by a spring. When a book sits on a table, it squeezes the atoms in the table together by a tiny amount. The atoms resist this squeezing and try to return the table to its natural thickness. The greater the table is compressed, the larger the normal force it creates. The matter in the table acts like a bunch of very stiff springs. You don't see the table compress because the amount of compression is very small.

VOCABULARY

normal force - the perpendicular force that a surface exerts on an object that is pressing on it.

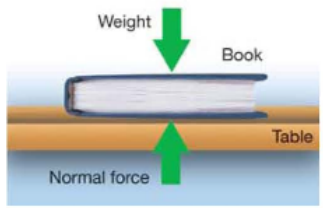


Figure 5.17: *The normal force and the weight are equal in strength and opposite in direction on a horizontal surface.*

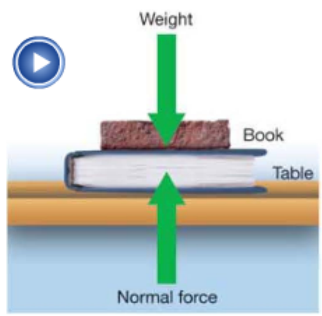


Figure 5.18: *The normal force is greater if a brick is placed on the book.*

The free-body diagram

Forces on a free-body diagram How can you keep track of many forces with different directions? The answer is to draw a **free-body diagram**. A free-body diagram contains only a single object, like a book or a table. All connections or supports are taken away and replaced by the forces they exert on the object. An accurate free-body diagram includes *every* force acting on an object, including weight, friction, and normal forces.

An example As an example of a free-body diagram, consider a stack of books weighing 30 newtons resting on a table that weighs 200 newtons. The books are on one corner of the table so that their entire weight is supported by one table leg. Figure 5.19 shows a free-body diagram of the forces acting on the table.

Finding the forces Because the table is in equilibrium, the net force on it must be zero. The weight of the books acts on the table making a 30 N force. The weight of the table acts on the floor. At every point where the table touches the floor (each leg) a normal force is created. The correct free-body diagram shows six forces. The normal force at each of the four legs is one-quarter the weight of the table (50 newtons). The leg beneath the book also supports the weight of the book (50 N + 30 N = 80 N).

The purpose of a free-body diagram By separating an object from its physical connections, a free-body diagram helps you identify all forces and where they act. A normal force is usually present when an object is in contact with another object or surface. Forces due to weight may be assumed to act directly on an object, often at its center.

Positive and negative forces There are two ways to handle positive and negative directions in a free-body diagram. One way is to make all upward forces positive and all downward forces negative. The second way is to draw all the forces in the direction you believe they act on the object. When you solve the problem, if you have chosen correctly, all the values for each force are positive. If one comes out negative, it means the force points in the opposite direction from what you guessed.

VOCABULARY

free-body diagram - a diagram showing all the forces acting on an object.

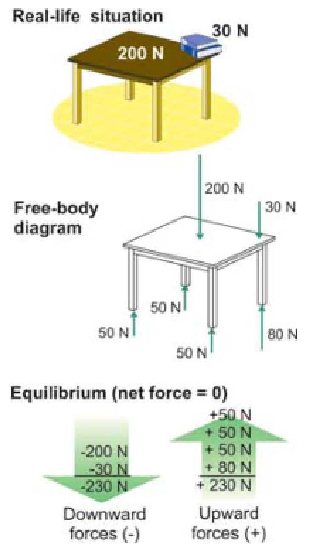


Figure 5.19: *A free-body diagram showing the forces acting on a table that has a stack of books resting on one corner.*

Solving Problems: Equilibrium

Two chains are used to support a small boat weighing 1,500 newtons. One chain has a tension of 600 newtons (Figure 5.20). What is the force exerted by the other chain?

1. Looking for: You are asked for an unknown tension in a chain.

2. Given: You are given the boat's weight in newtons and the tension in one chain in newtons.

3. Relationships: The net force on the boat is zero.

4. Solution: Draw a free-body diagram.
The force of the two chains must balance the boat's weight.
$600\text{ N} + F_{chain2} = 1{,}500\text{ N}$ $F_{chain2} = 900\text{ N}$

Your turn...

a. A person with a weight of 400 N is sitting motionless on a swing (Figure 5.21). For the swing to be in equilibrium, what is the tension force in each rope holding up the swing?

b. A heavy box weighing 1,000 N sits on the floor. You press down on the box with a force of 450 N. What is the normal force on the box?

c. A cat weighing 40 N stands on a chair. If the normal force on each of the cat's back paws is 12 N, what is the normal force on each front paw? (You can assume the force is the same on each front paw.)

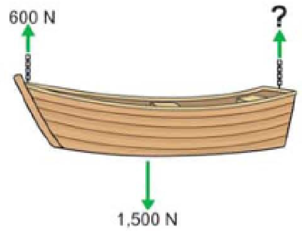


Figure 5.20: *What is the force exerted by the other chain that is supporting the boat?*

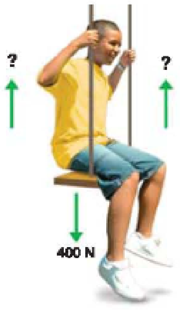


Figure 5.21: *What is the tension force in each rope holding up the swing?*

SOLVE FIRST LOOK LATER

(a) The upward force from both ropes must be 400 N, so the force in each rope is 200 N. (b) 1,450 N; (c) 8 N

Section 5.3 Review

1. What is the relationship between net force and balanced forces?
2. Make two diagrams. The first diagram should show a net force of zero on an object and the other diagram should show a net force that is not zero.
3. If an object is accelerating, can the net force acting on it ever be zero? Explain your answer.
4. If you push down on a table with a force of 5 newtons, what is the normal force pushing back on you?
5. The diagram in Figure 5.22 shows three forces acting on a pencil. What is the net force acting on the pencil?
6. If an object is in equilibrium,
   a. the net force on the object is zero.
   b. the object has zero total mass.
   c. no forces are acting on the object.
   d. only normal forces are acting on the object.
7. A train is climbing a gradual hill. The weight of the train creates a downhill force of 150,000 newtons. Friction creates an additional force of 25,000 newtons acting in the same direction (downhill) (Figure 5.23). How much force does the train's engine need to create so the train is in equilibrium (going uphill at constant speed)?
8. Draw a free body diagram of your own body sitting on a stool. Include all forces acting on your body.
9. If a force has a negative value, such as −100 N, that means the force
   a. is less than 100 N in strength.
   b. acts in the opposite direction from a +100 N force.
   c. is a normal force.
10. A child weighing 200 newtons is sitting in the center of a swing. The swing is supported evenly by two ropes, one on each side. What is the tension force in one of the ropes?

Figure 5.22: *Question 5.*

Figure 5.23: *Question 7.*

Chapter 5 Assessment

Vocabulary

Select the correct term to complete the sentences.

balanced forces	compression	equilibrium
free-body diagram	friction	net force
newton	normal force	pound
sliding friction	static friction	tension
weight	force	

Section 5.1

1. A(n) ____ is an action that can change an object's speed, direction, or both.
2. The English unit of force equal to 4.448 newtons is the ____.
3. The SI unit of force needed to accelerate a 1-kg mass at 1 m/s each second is the ____.
4. Squeezing creates ____ in a spring.
5. A pulling force carried by a rope is called ____.

Section 5.2

6. ____ is a force that always resists the relative motion of objects or surfaces.
7. A frictional force that occurs when one surface slides over another is called ____.
8. ____ is a frictional force between two nonmoving surfaces.

Section 5.3

9. When forces add up to a net force equal to zero they are called ____.
10. When all forces on an object are balanced, the object is in ____.
11. The perpendicular force exerted by a surface on an object pressing against it is called the ____.
12. A drawing representing all forces acting on an object is called a(n) ____.
13. The sum of all forces acting on an object is called the ____.

Concepts

Section 5.1

1. Describe one situation in which forces are created.
2. Name the four fundamental forces of nature, the forces from which all others are derived.
3. Why is weight considered a force?
4. Forces cause changes to the motion of objects. Name a force and describe two changes it makes.
5. What two pieces of information do you need to describe a force?
6. Draw the following force vectors and show the scale you use.
   a. 20 N west
   b. 4 N southeast
7. Name one contact force and one force that acts through a force field.
8. What happens to a spring's force if you stretch it more?
9. Distinguish between tension, compression, and extension.
10. Which of the following is most often used to change the direction of a force, but not the strength of the force?
    a. a ball bearing
    b. a rope
    c. a spring
    d. a parachute
11. You know the relationship between weight and mass at the surface of the Earth. Describe this relationship on the Moon.

12. Identify which of the following are units of force (F) and which are units of mass (M).

a. ____ kilogram c. ____ pound

b. ____ newton d. ____ gram

Section 5.2

13. Give a reasonable explanation for why the friction is so low between an ice skate blade and the ice.

14. Does it require more force to start an object sliding or to keep it sliding? Explain your answer.

15. Why is it much easier to slide a cardboard box when it is empty compared to when it is full of heavy books?

16. Explain two ways friction can be reduced.

17. Explain how friction keeps a nail in place in a block of wood. If you try to pull out the nail, which way does the friction act?

18. Name two types of energy generated by friction and give an example of each.

19. Is friction something we always want to reduce? Explain.

Section 5.3

20. If the net force on an object is zero, can the object be moving? Explain.

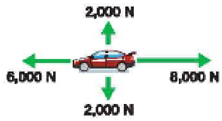
21. Standing on Earth, gravity exerts a downward force on you, yet you don't fall toward the center of the planet.

a. Name the other force that acts on you and keeps you in equilibrium.

b. What is the direction of the other force?

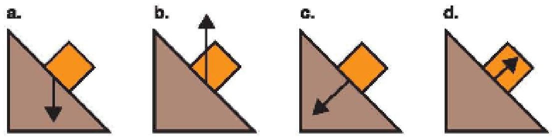
c. What do you know about the strength of this other force?

22. Describe the motion of the race car shown in the graphic. Assume the car is moving forward. Is it speeding up or slowing down?



23. What are the four main forces acting on an airplane in flight? If the plane accelerates forward, which two forces must be out of balance? In order for the plane to fly on a level path, which two forces must be in balance?

24. Which of the following diagrams correctly shows the normal force on the block of wood sliding down the incline?



25. Draw a free-body diagram for the forces acting on the parachutist shown. Don't forget about air friction!

Problems

Section 5.1

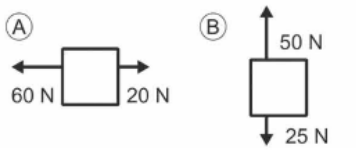
1. Calculate the weight of a 66-newton bowling ball in pounds.
2. A frozen turkey bought in Canada is labeled "5.0 kilograms." This is a measurement of its mass. What is its weight in newtons?
3. What is the mass, in kilograms, of a large dog that weighs 441 newtons?
4. How much does a 40-kg student weigh on Earth in newtons?
5. How much mass, in kilograms, does a 50,000-N truck have?
6. An astronaut has a mass of 70 kilograms on Earth. What would her mass be on Mars? What would her weight be on Mars? The value of gravity (g) on Mars is 3.7 m/s^2.
7. Using a scale of 1 cm = 5 N, draw force vectors representing a +20 N force and a –10 N force.
8. A spring is stretched 15 cm by a 45-N force. How far would the spring be stretched if a 60-N force were applied?
9. You and your friend pull on opposite ends of a rope. You each pull with a force of 10 newtons. What is the tension in the rope?
10. Two friends decide to build their strength by having a tug of war each day. They each pull with a force of 200 N.
    a. How much tension is in the rope?
    b. One day, one of the friends is sick and cannot work out. The other friend decides to build strength by tying the rope around a tree and pulling on the rope. How much must the single friend pull in order to get the same workout as he normally does? What is the tension on the rope? Explain.
    c. In both cases above, what is the net force on the rope if (a) neither person is moving, and (b) the tree does not move?

Section 5.2

11. Thomas pushes a 250-N box across a wooden floor at a constant speed using 75 N of force. If a second box of the same weight is stacked on top of the first, how much force would Thomas need to push the two boxes across the same floor?
12. Your backpack weighs 50 N. You pull it across a table at a constant speed by exerting a force of 20 N to the right. Draw a free-body diagram showing all four forces on the backpack. State the strength of each force.
13. You exert a 50-N force to the right on a 300-N box that is on a table. However, the box does not move. Draw a free-body diagram for the box. Label all the forces and state their strengths. Explain why the box doesn't move.

Section 5.3

14. Find the net force on each box.



15. A 20-kilogram monkey hangs from a tree limb by both arms. Draw a free-body diagram showing the forces on the monkey. Hint: 20 kilograms is not a force!
16. The weight of a book resting on a stationary table is 9 N. How much is the normal force on the book? What would you need to do to increase the normal force on the book?
17. Is it possible to arrange three forces of 100 N, 200 N, and 300 N so they are in equilibrium? If so, draw a diagram.

18. You weigh a bear by making him stand on four scales as shown. Draw a free-body diagram showing all the forces acting on the bear. If his weight is 1,500 newtons, what is the reading on the fourth scale?

Applying Your Knowledge

Section 5.1

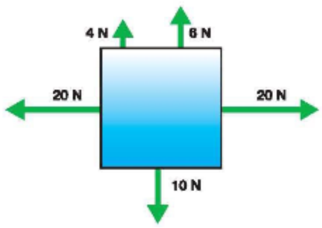
1. What is the weight of your favorite animal at different places in the universe?
   a. First, find your favorite animal's mass in kilograms. (1 pound = 0.454 kilogram; 2.2 pounds = 1 kilogram)
   b. Then, find the values of gravitational force (g) on five different planets or moons. The next page has values for g for the planets in our solar system in units of N/kg.
   c. Make a table that lists g for each planet or moon and your animal's weight in Newtons on each.
2. Use the data in the table on the next page to answer the following questions.
   a. You know that mass is related to the strength of an object's gravitational force. Does the data in the table support this statement? Support your answer with an explanation.
   b. Is gravitational force related to the number of moons that a planet has?
   c. Is gravitational force related to how far a planet is from the Sun?
   d. Now, come up with your own question and answer it using the data in the table.

Section 5.2

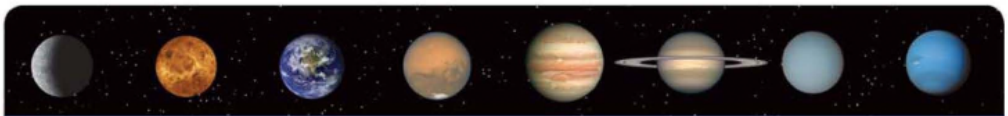
3. When an ice skater is on ice, a small amount of melting occurs under the blades of the skates. How does this help the skater glide? Your answer should discuss at least one type of friction.
4. Joints, such as knees and elbows, are designed to move freely. Find out how friction is reduced in a joint.
5. When on a mission, astronauts experience weightlessness.
   a. Research weightlessness. Define it in terms of the forces experienced by an astronaut.
   b. Research the effects of weightlessness on people and what astronauts do to counter those effects.

Section 5.3

6. Use the diagram to answer the following questions.



   a. Is the object shown in the diagram in equilibrium? Why or why not?
   b. Redraw this free-body diagram in a way that shows that the box will move to the right.
   c. Redraw this free-body diagram so that the box will move downward.



	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune
Diameter *(km)*	4,879	12,104	12,756	6,792	142,984	120,536	51,118	49,528
Mass *(kg)*	3.3×10^{23}	4.9×10^{24}	6.0×10^{24}	6.4×10^{23}	1.9×10^{27}	5.7×10^{26}	8.7×10^{25}	1.2×10^{26}
Density *(g/cm³)*	5.42	5.24	5.52	3.93	1.32	0.69	1.27	1.64
Average distance from the Sun *(km)*	58 million	108 million	150 million	228 million	778 million	1.43 billion	2.87 billion	4.50 billion
Moons *(number of)*	0	0	1	2	63	60	27	13
Gravitational force *(N/kg)*	3.7	8.9	9.8	3.7	23.1	9.0	8.7	11.0
Surface temperature *(°C)*	−170 to +450	+465	−88 to +48	−89 to −31	−110	−139	−195	−200
Rotation period *(Earth days)*	59	243	1	1.03	0.41	0.44	0.72	0.67
Revolution period *(Earth years)*	0.24	0.62	1	1.9	12	29.5	84	165
Major gases in atmosphere	Trace He, H_2, O_2, Na	CO_2	N_2, O_2	CO_2	H_2, He, CH_4, NH_3	H_2, He, CH_4, NH_3	H_2, He, CH_4, NH_3	H_2, He, CH_4, NH_3
Orbital velocity *(km/s)*	47.89	35	29.80	24.14	13.1	9.7	6.80	5.43

Planet photos courtesy of NASA/JPL. Planets not shown to scale.

Lesson 5.3: Forces and Equilibrium

A cup placed on a table top is at rest. A shopping cart rolling across a parking lot is in motion. Forces are acting on both the cup and the shopping cart, but the result of these forces is not the same. When forces act on an object, The object either remains at rest or it is set in motion. The outcome depends on the net force, which is the sum of all forces acting on an object. In this lesson students learn to calculate net force and to explain the meaning of equilibrium. *Students also learn about normal forces and how to draw free-body diagrams.*

Start the lesson

Connect to Prior Knowledge: Positive and Negative Numbers

When adding forces, it is important for students to understand how to add positive and negative numbers. Students were introduced to positive and negative position as they completed Investigation 3A. Try the problems below to find out if your students have mastered how to solve mathematical operations with negative numbers.

$5+(-3)=2$ $\quad -24-12=-36$ $\quad 16-18=-2$ $\quad 2-(-5)=7$ $\quad -8+12=4$

If students are still unclear about positive and negative numbers, draw a number line with values from –10 to +10. Label the origin. Model addition and subtraction with positive and negative numbers along the line.

Then create an x-y grid, showing four quadrants on the board. Place a dot anywhere in each quadrant and ask students, "Is the value of x positive or negative in the first quadrant?" and "What about the value of y?" Ask these questions for each quadrant. Record students' responses on the board using plus and minus signs for x and y.

Motivate: What's my balance?

Use play money to teach students about positive and negative balances in an account. A few days before starting this lesson, distribute an equal sum of play money to each student. Assign a cost to tasks like sharpening a pencil or speaking without recognition. Then, assign a value for rewards for when students turn in their homework on time or do other things that you designate. Instruct students to keep a register of all their losses and gains to determine their balance at the end of one week. Did any students have a zero balance? If so, have those students describe their balance in terms of the vocabulary discussed in this lesson.

vo·cab·u·lar·y

net force - the sum of all forces acting on an object.

balanced forces - combined forces that result in a zero net force on an object.

equilibrium - the state in which the net force on an object is zero. or·i·gin

normal force - the perpendicular force that a surface exerts on an object that is pressing on it.

free-body diagram - a diagram showing all the forces acting on an object.

Free-Body Diagrams

Cooperative Learning

Select items in your classroom for which students will draw free-body diagrams. Use index cards to label some of the forces acting upon each object. Leave at least one force unidentified for each object. Have students work in small groups to identify the total forces acting upon each object, and draw its free-body diagram.

After each team has completed their drawings, have each group choose the free-body diagram for one object to present to the class. Tell students to use either chart paper or the board to make a large diagram. Then have students identify which forces were provided and those which were unknown. Each group should total the downward forces, and then the upward forces next to their diagrams. Have members from each group answer the following questions.

1. How did you determine the value of the unknown forces?
2. What is the net force acting on your object?
3. What does a net force equal to zero imply?

Present the content

Demonstration: Equilibrium and Tug of War

Choose two student volunteers to demonstrate balanced and unbalanced forces. Select students who appear to have approximately equal weight and strength. Provide the students a rope with a flag tied in the middle. Privately instruct them to play tug of war with one student winning, and then the other. Be sure they understand the need for periods where it appears that both students are at a stalemate.

Ask the class, "Who won the battle?" Students should observe that each student won a turn. Then ask, "Was there ever a time when neither was winning?" Students should observe that neither student was winning when the flag in the middle did not move. Ask, "What can you say about the forces when the flag was not moving?" The forces were equal but in opposing directions. Then have students think about what they observed as one or the other student won the battle. They should infer that the forces were unbalanced.

Use this demonstration to reinforce the meaning of equilibrium, balanced forces, and net force. Remind students that when forces are balanced they add up to a net force of zero.

Check for understanding

Exit Slip

Suppose a friend challenges you to an arm wrestling competition. At first, your friend seems to have a clear advantage, as he nearly pins your hand to the table within seconds of starting the match. However, you are able to overpower him long enough to get back to your starting position. In the end, he wins. How could you describe the details of the competition in terms of balanced and unbalanced forces? (The forces were balanced when both competitors' hands were locked together at the starting position and not moving from side to side. As one competitor gained the advantage and was able to overpower the other, the forces were no longer balanced.)

Reteach

Review the forces discussed in Chapter 5. Have students create study cards for each of these forces. A sample card may include the name of the force and a description or definition created by the student. Also, have students sketch a visual description beneath the definition or on the back of the card. Then have students work with a partner to review what they have learned.

Standardized Test Practice

During an after-school visit to the dentist, Kim notices her favorite magazine resting on a table in the waiting area. Which of the following statements offers the best explanation for what must happen in order for the magazine to move?

a. The magazine will move if the normal force acts on it.

b. The force of gravity must act on the magazine in order for it to move.

c. The magazine will move if subjected to an unbalanced force.

d. The magazine will move if the force of friction between itself and the table is increased.

The correct answer is (c). The magazine resting on the table is at equilibrium, meaning its net force is equal to zero. If an unbalanced force is applied to the magazine, its net force is no longer zero, and a change in its motion results.

The magazine is supported by the table, which exerts an upward (normal) force on it. This force is balanced by the weight of the magazine, which pushes it downward onto the surface of the table. The force of gravity acts upon objects at rest as well as those in motion. In either case, the magazine will not move unless the forces acting upon it are unbalanced, so answers (a) and (b) are incorrect.

Changes in friction will not affect motion as long as the net force acting on the magazine is zero. Therefore, (d) is also an incorrect response.