2 MECHANICAL EQUILIBRIUM

Objectives

- Distinguish between force and net force. (2.1)
- Describe the equilibrium rule and give examples. (2.2)
- Distinguish between support force and weight. (2.3)
- Give examples of moving objects that are in equilibrium. (2.4)
- Determine the resultant of a pair of parallel or non-parallel vectors. (2.5)

Suggest to your students that they read the chapters quickly, but more than once. Physics is learned by going over the same material many times. Each time it makes a little more sense. (That's also the best way to learn a foreign language: total immersion.) So don't worry about understanding things quickly. Just keep reading. Understanding will come!

PAUL

discover!

MATERIALS strong piece of rope

EXPECTED OUTCOME The two people pulling the ends of the rope will be unable to straighten out the deflection caused by the third person's little finger.

ANALYZE AND CONCLUDE

1. No, it does not remain straight.
2. Predictions will vary.
3. In order for an object to be in equilibrium, the sum of the forces on the object must equal zero ($\Sigma F = 0$).

2 MECHANICAL EQUILIBRIUM

THE BIG IDEA An object in mechanical equilibrium is stable, without changes in motion.

It's good when your personal life is stable—when things important to you are in balance. It's also nice when the needs of family and friends are in harmony. Financially, we prefer our expenses to be balanced by earnings. Economists are concerned with the balance between the inflow and outflow of goods. These examples illustrate the idea of *equilibrium.* In nature we see an energy equilibrium when energy radiated away from Earth is balanced by the input of solar energy from the sun. Whenever a glass thermometer acquires the same temperature as the object being measured, we have thermal equilibrium. There are many forms of equilibrium. In this chapter we will be concerned with *mechanical equilibrium.* Things in mechanical equilibrium are stable, without changes of motion. The rocks shown at right are in mechanical equilibrium. An unbalanced external force would be needed to change their resting state.

discover!

How Do You Know When an Object Is in Equilibrium?

1. Stretch a strong rope between another student and yourself.
2. With the two of you pulling hard on the rope, have a third person push down on the center of the rope with his or her little finger.
3. Try to make the rope straight while the person continues to push down on the center of the rope.

Analyze and Conclude

1. **Observing** Did the rope remain straight with the application of the small downward force on the center of the rope?
2. **Predicting** Is there any way to make the rope straight as long as someone is pushing down on the center of the rope?
3. **Making Generalizations** What do you think are the conditions necessary for equilibrium?

2.1 Force

A **force** is a push or a pull. A force of some kind is always required to change the state of motion of an object. The state of motion may be one of rest or of moving uniformly along a straight-line path. For example, a hockey puck at rest on ice remains at rest until a force is exerted on it. Once moving, a hockey puck sliding along the ice will continue sliding until a force slows it down. **A force is needed to change an object's state of motion.**

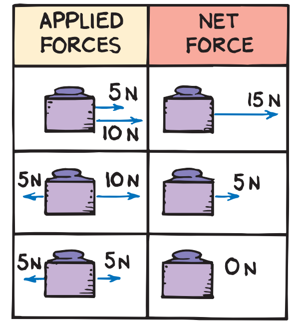
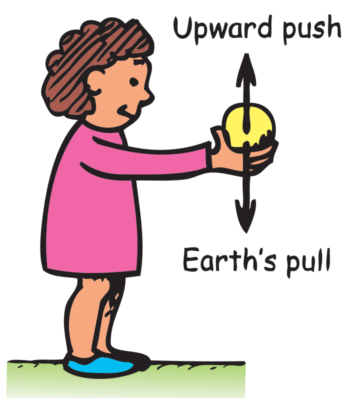


FIGURE 2.1 ▲
The net force depends on the magnitudes and directions of the applied forces.

The superscript 2.1.1 refers to a note to the text. Notes are listed in Appendix G.

Net Force Most often, more than one force acts on an object. The combination of all forces acting on an object is called the **net force.** The net force on an object changes its motion.

For example, suppose you pull horizontally on an object with a force of 10 pounds. If a friend assists you and also pulls in the same direction with a force of 5 pounds, then the net force is the sum of these forces, or 15 pounds. The object moves as if it were pulled with a single 15-pound force. However, if your friend pulls with a force of 5 pounds in the opposite direction, then the net force is the difference of these forces, or 5 pounds toward you. The resulting motion of the object is the same as if it were pulled with a single 5-pound force. This is shown in Figure 2.1, where instead of pounds, the scientific unit of force is used—the newton, abbreviated N.[2.1.1]



◀ FIGURE 2.2
When the girl holds the rock with as much force upward as gravity pulls downward, the net force on the rock is zero.

When you hold a rock at rest in your hand, you are pushing upward on it with as much force as Earth's gravity pulls down on it. If you push harder, it will move upward; if you push with less force, it will move downward. But just holding it at rest, as shown in Figure 2.2, means the upward and downward forces on it add to zero. The net force on the rock is zero.

2.1 Force

Key Terms
force, net force, vector, vector quantity, scalar quantity

We define force in this section as a push or pull. In Chapter 7, we'll extend this definition to be an interaction between one object and another. For now, push or pull is sufficient.
PAUL

▶ **Teaching Tip** Without excess explanation, go right into newtons as a measure of force (just as you'll mention meters rather than feet for a unit of distance). If students have trouble with newtons, just tell them it's scientific language for what they call pounds. In fact, 10 N = 2.2 pounds.

▶ **Teaching Tip** Introduce the idea of net force by placing an object on your table and pushing it. State that, neglecting friction, if you push it to the right with a force of 10 N, the net force is 10 N. Ask what the net force would be if a student simultaneously pushed it to the left with a force of 10 N. (Zero) With a force of 4 N? (6 N to the right) State that the block would accelerate no differently if pushed with two forces that produce a 6-N net force, or pushed with a single applied 6-N force. The two are equivalent.

▶ **Teaching Tip** Distinguish between net force and force with Figure 2.1.

▶ **Teaching Tip** Explain that the term *net force* is the same as *resultant force* and is also the same as *vector sum of all forces*.

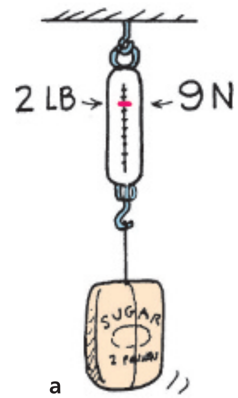
Vector quantities are introduced in terms of force. Velocity vectors are postponed until Chapter 4. (One step at a time!) We begin with parallel force vectors, the easiest to understand. Vectors at an angle are discussed in Section 2.5.

PAUL

CONCEPT CHECK A force is needed to change an object's state of motion.

Teaching Resources

- **Reading and Study Workbook**
- **Transparency *1***
- **Presentation*EXPRESS***
- **Interactive Textbook**

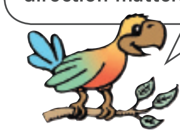


a

b

FIGURE 2.3 ▶
a. The upward tension in the string has the same magnitude as the weight of the bag, so the net force on the bag is zero. **b.** Burl Grey, who first introduced the author to the concept of tension, shows a 2-lb bag producing a tension of 9 newtons. (The weight is actually slightly more than 2 lb, and the tension slightly more than 9 N.)

Scalars can be added, subtracted, multiplied, and divided like ordinary numbers. When 2 liters of water are added to 3 liters of water, the result is 5 liters. But when something is pulled by two forces, one 2 N and the other 3 N, the result may or may not be 5 N. With vector quantities, direction matters.



Tension and Weight If you tie a string around a 2-pound bag of sugar and suspend it from a scale, a spring in the scale stretches until the scale reads 2 pounds, as shown in Figure 2.3. The stretched spring is under a "stretching force" called *tension*. A scale in a science lab is likely calibrated to read this 2-pound force as 9 newtons. Both pounds and newtons are units of weight, which, in turn, are units of force. The bag of sugar is attracted to Earth with a gravitational force of 2 pounds—or, equivalently, 9 newtons. Suspend twice as much sugar from the scale and the reading will be 18 newtons.

There are two forces acting on the bag of sugar—tension force acting upward and weight acting downward. The two forces on the bag are equal and opposite, and they cancel to zero. The net force on the bag is zero, and it remains at rest.

Force Vectors In Figures 2.1 and 2.2, forces are represented by arrows. When the length of the arrow is scaled to represent the amount (magnitude) of the force and the direction of the arrow points in the direction of the force, we refer to the arrow as a vector.[2.1.2] A **vector** is an arrow that represents the magnitude and direction of a quantity. A **vector quantity** is a quantity that needs both magnitude and direction for a complete description. Force is an example of a vector quantity. By contrast, a **scalar quantity** is a quantity that can be described by magnitude only and has no direction. Time, area, and volume are scalar quantities. (We'll return to vectors in Chapter 5.)

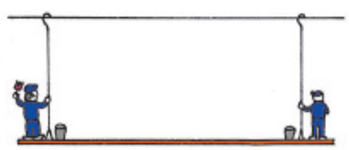
FIGURE 2.4 ▲
This vector, scaled so that 1 cm = 20 N, represents a force of 60 N to the right.

CONCEPT CHECK **How can you change an object's state of motion?**

Personal Essay

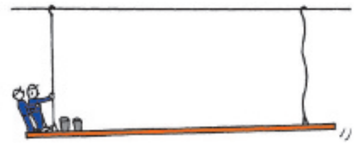
When I was in high school, my counselor advised me not to enroll in science and math classes, but to instead focus on what seemed to be my gift for art. I took this advice. I was then interested in drawing comic strips and in boxing, neither of which earned me much success. After a stint in the U.S. Army, I tried my luck at sign painting, and the cold Boston winters drove me south to Miami, Florida. There, at age 26, I got a job painting billboards and met a new friend, Burl Grey, a sign painter with an active intellect. Burl, like me, had never studied physics in high school. But he was passionate about science in general. He shared that passion with me by asking many fascinating science questions as we painted together.

I remember Burl asking me questions about the tensions in the ropes that held up the scaffold we stood on. The scaffold was simply a heavy horizontal plank suspended by a pair of ropes at each end. Burl twanged the rope nearest his end of the scaffold and asked me to do the same with mine. He was comparing the tensions in the two ropes—to determine which was greater. Burl was heavier than I was, and he guessed that the tension in his rope was greater. Like a more tightly stretched guitar string, the rope with greater tension twangs at a higher pitch. That Burl's rope had a higher pitch seemed reasonable because his rope supported more of the load.



When I walked toward Burl to borrow one of his brushes, he asked if tensions in the ropes had changed. Did tension in his rope increase as I moved closer? We agreed that it should have because even more of the load was then supported by Burl's rope. How about my rope? Would its tension decrease? We agreed that it would, for it would be supporting less of the total load. I was unaware at the time that we were discussing physics.

Burl and I used exaggeration to bolster our reasoning (just as physicists do). If we both stood at an extreme end of the scaffold and leaned outward, it was easy to imagine the opposite end of the staging rising like the end of a seesaw, with the opposite rope going limp. Then there would be no tension in that rope. We then reasoned the tension in my rope would gradually decrease as I walked toward Burl. It was fun posing such questions and seeing if we could answer them.



A question that we couldn't answer was whether or not the decrease of tension in my rope when I walked away from it would be *exactly* compensated by a tension increase in Burl's rope. For example, if the tension in my rope underwent a decrease of 50 newtons, would Burl's rope gain 50 newtons? (We talked pounds back then, but here we use the scientific unit of force, the *newton*—abbreviated N.) Would the gain be *exactly* 50 N? And if so, would this be a grand coincidence? I didn't know the answers until more than a year later, when Burl's stimulation resulted in my leaving full-time painting and going to college to learn more about science.[2.1.3]

At college I learned that any object at rest, such as the sign-painting scaffold that supported us, experiences no net force. It is said to be in *equilibrium*. That is, all the forces that act on it balance to zero ($\Sigma F = 0$). So the sum of the upward forces supplied by the supporting ropes do indeed add up to the downward forces of our weights plus the weight of the scaffold. A 50-N loss in one would be accompanied by a 50-N gain in the other.

I tell this true story to make the point that one's thinking is very different when there is a rule to guide it. Now when I look at any motionless object, I know immediately that all the forces acting on it cancel out. We view nature differently when we know its rules. It makes nature seem simpler and easier to understand. Without the rules of physics, we tend to be superstitious and see magic where there is none. Quite wonderfully, everything is beautifully connected to everything else by a surprisingly small number of rules. The rules of nature are what the study of physics is about.

Of particular interest to me in Chapter 2 is this Personal Essay, which relates to events that inspired me to pursue a life in physics—my meeting with influential Burl Grey on the sign-painting stages of Miami, Florida (and Jacque Fresco, also in Miami). Relative tensions in supporting cables is what first caught my interest in physics, and I hope to instill the same interest in your students.

PAUL

2.2 Mechanical Equilibrium

Key Terms
mechanical equilibrium, equilibrium rule

You can find more on the equilibrium rule in the Concept-Development Practice Book. (Not using the Practice Book is like teaching swimming away from water. This is an important book—my most imaginative and pedagogically useful tool for student learning!)
PAUL

CONCEPT CHECK You can express the equilibrium rule mathematically as $\Sigma F = 0$.

Teaching Resources
- **Reading and Study Workbook**
- **Concept-Development Practice Book** ***2-1***
- **Laboratory Manual** ***2***
- **Presentation*EXPRESS***
- **Interactive Textbook**
- **Next-Time Question** ***2-1***

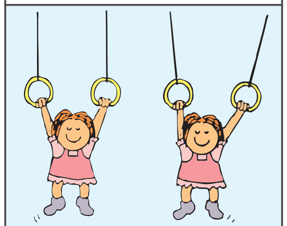
2.2 Mechanical Equilibrium

Mechanical equilibrium is a state wherein no physical changes occur; it is a state of steadiness. Whenever the net force on an object is zero, the object is said to be in mechanical equilibrium—this is known as the **equilibrium rule.**[2.2] **You can express the equilibrium rule mathematically as**

$$\Sigma F = 0$$

The symbol Σ stands for "the sum of" and F stands for "forces." (Please don't be intimidated by the expression $\Sigma F = 0$, which is physics shorthand that says a lot in so little space—that all the forces acting on something add vectorially to zero.) For a suspended object at rest, like the bag of sugar mentioned earlier, the rule states that the forces acting upward on the object must be balanced by other forces acting downward to make the vector sum equal zero. (Vector quantities take direction into account, so if upward forces are positive, downward ones are negative, and when summed they equal zero.)

think!



Consider the gymnast above hanging from the rings. If she hangs with her weight evenly divided between the two rings, how would scale readings in both supporting ropes compare with her weight? Suppose she hangs with slightly more of her weight supported by the left ring. How would a scale on the right read?
Answer: 2.2

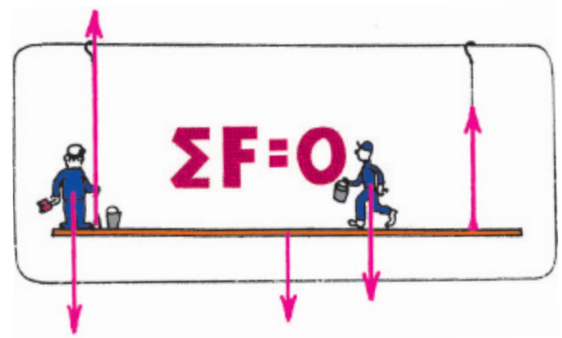
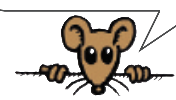


FIGURE 2.5
The sum of the upward vectors equals the sum of the downward vectors. $\Sigma F = 0$, and the scaffold is in equilibrium.

If you look carefully at bridges and other structures around you, you'll see evidence of $\Sigma F = 0$.



In Figure 2.5 we see the forces of interest to Burl and Paul on their sign-painting scaffold. The sum of the upward tensions is equal to the sum of their weights plus the weight of the scaffold. Note how the magnitudes of the two upward vectors equal the magnitude of the three downward vectors. Net force on the scaffold is zero, so we say it is in mechanical equilibrium.

CONCEPT CHECK **How can you express the equilibrium rule mathematically?**

2.3 Support Force

Consider a book lying at rest on a table, as shown in Figure 2.6a. The book is in equilibrium. What forces act on the book? One is the force due to gravity—the weight of the book. Since the book is in equilibrium, there must be another force acting on it to produce a net force of zero—an upward force opposite to the force of gravity.

Where is the upward force coming from? It is coming from the table that supports the book. We call this the **support force**—the upward force that balances the weight of an object on a surface. A support force is often called the *normal force*.[2.3.1] **For an object at rest on a horizontal surface, the support force must equal the object's weight.** So in this case, the support force must equal the weight of the book. We say the upward support force is positive and the downward weight is negative. The two forces add mathematically to zero. So the net force on the book is zero. Another way to say the same thing is $\Sigma F = 0$.

To better understand that the table pushes up on the book, compare the case of compressing a spring, shown in Figure 2.6b. If you push the spring down, you can feel the spring pushing up on your hand. Similarly, the book lying on the table compresses atoms in the table, which behave like microscopic springs. The weight of the book squeezes downward on the atoms, and they squeeze upward on the book. The compressed atoms produce the support force.

When you step on a bathroom scale, two forces act on the scale, as shown in Figure 2.7. One force is the downward pull of gravity, your weight, and the other is the upward support force of the floor. These forces compress a mechanism (in effect, a spring) that is calibrated to show your weight. So the scale shows the support force. When you're standing on a bathroom scale at rest, the support force and your weight have the same magnitude.[2.3.2]

CONCEPT CHECK: For an object at rest on a horizontal surface, what is the support force equal to?

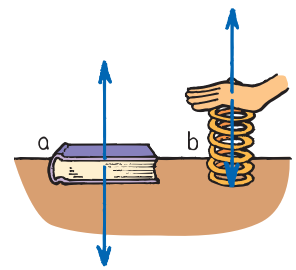


FIGURE 2.6 ▲
a. The table pushes up on the book with as much force as the downward weight of the book. **b.** The spring pushes up on your hand with as much force as you push down on the spring.

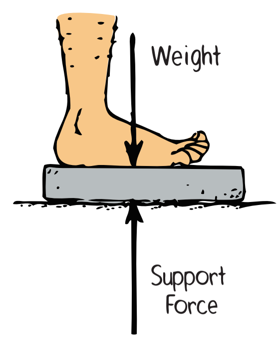


FIGURE 2.7 ▲
The upward support force is as much as the downward pull of gravity.

think!

What is the net force on a bathroom scale when a 110-pound person stands on it? *Answer: 2.3.1*

Suppose you stand on two bathroom scales with your weight evenly distributed between the two scales. What is the reading on each of the scales? What happens when you stand with more of your weight on one foot than the other? *Answer: 2.3.2*

2.3 Support Force

Key Term
support force

If you have a pair of bathroom scales, a student standing with one foot on each will confirm that the two weight readings add up to the student's weight. Do not ask a student who may be self-conscious about his or her weight to try this! (During my elementary school years, the most stressful day of the year was the day the school nurse had us stand on a scale while she called out the weight to the teacher. This fear continued until I reached 100 lb. in high school. I overcame it at the age of 16 by winning the New England Amateur Athletic Association silver medal for boxing in the 112-lb. class. A long reach for a tall skinny body turned out to be an advantage!)

PAUL

▶ **Teaching Tip** The normal force on an object on an inclined plane is perpendicular to the plane, but not opposite the vertical force of gravity.

CONCEPT CHECK: For an object at rest on a horizontal surface, the support force must equal the object's weight.

Teaching Resources
- **Reading and Study Workbook**
- **Presentation*EXPRESS***
- **Interactive Textbook**

2.4 Equilibrium for Moving Objects

▶ **Teaching Tip** Mention that if you're in the car of a smoothly moving train and you balance a deck of cards on a table, they are in equilibrium whether the train is in motion or not. If there is no change in motion (i.e., acceleration), the cards "don't know the difference."

▶ **Teaching Tip** Drag a block at constant velocity across your lecture table. Acknowledge the force of friction, and how it must exactly counter your pulling force. Show the pulling force with a spring balance. Now, since the block moves without changing speed, ask for the magnitude of the friction force. It must be equal and opposite to the force indicated by the scale reading. So the net force is zero. While sliding, the block is in dynamic equilibrium. That is, $\Sigma F = 0$.

2.4 Equilibrium for Moving Objects

think!

An airplane flies horizontally at constant speed in a straight-line direction. Its state of motion is unchanging. In other words, it is in equilibrium. Two horizontal forces act on the plane. One is the thrust of the propeller that pulls it forward. The other is the force of air resistance (air friction) that acts in the opposite direction. Which force is greater? *Answer: 2.4*

When an object isn't moving, it's in equilibrium. The forces on it add up to zero. But the state of rest is only one form of equilibrium. An object moving at constant speed in a straight-line path is also in a state of equilibrium. Once in motion, if there is no net force to change the state of motion, it's in equilibrium.

Equilibrium is a state of no change. A hockey puck sliding along slippery ice or a bowling ball rolling at constant velocity is in equilibrium—until either experiences a non-zero net force. Whether at rest or steadily moving in a straight-line path, the sum of the forces on both is zero: $\Sigma F = 0$.

Interestingly, an object under the influence of only one force cannot be in equilibrium. Net force in that case is not zero. Only when there is no force at all, or when two or more forces combine to zero, can an object be in equilibrium. We can test whether or not something is in equilibrium by noting whether or not it undergoes changes in motion.

Figure 2.8 shows a desk being pushed horizontally across a factory floor. If the desk moves steadily at constant speed, without change in its motion, it is in equilibrium. This tells us that more than one horizontal force acts on the desk—likely the force of friction between the bottom of the desk and the floor. Friction is a contact force between objects that slide or tend to slide against each other (more about friction in Chapter 6). The fact that the net force on the desk equals zero means that the force of friction must be equal in magnitude and opposite in direction to our pushing force.

FIGURE 2.8 ▶
When the push on the desk is as much as the force of friction between the desk and the floor, the net force is zero and the desk slides at an unchanging speed.

Types of equilibrium include static (at rest) and dynamic (moving at constant speed in a straight-line path).

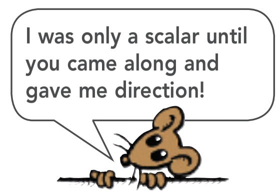
Objects at rest are said to be in static equilibrium; objects moving at constant speed in a straight-line path are said to be in dynamic equilibrium. Both of these situations are examples of mechanical equilibrium. As mentioned at the beginning of this chapter, there are other types of equilibrium. In Chapter 11 we'll discuss another type of mechanical equilibrium—rotational equilibrium. Then in Chapter 21 when we study heat, we'll discuss thermal equilibrium, where temperature doesn't change.

The equilibrium rule, $\Sigma F = 0$, provides a reasoned way to view all things at rest—balanced rocks, objects in your room, or the steel beams in bridges. Whatever their configuration, if at rest, all acting forces always balance to zero. The same is true of objects that move steadily, not speeding up, slowing down, or changing direction. For such moving things, all acting forces also balance to zero. The equilibrium rule is one that allows you to see more than meets the eye of the casual observer. It's good to know the rule for the stability of things in our everyday world. Physics is everywhere.

CONCEPT CHECK How are static and dynamic equilibrium different?

2.5 Vectors

Look at Figure 2.9. When gymnast Nellie Newton is suspended by a single vertical strand of rope (Figure 2.9a), the tension in the rope is 300 N, her weight. If she hangs by two vertical strands of rope (Figure 2.9b), the tension in each is 150 N, half her weight. Rope tensions pull her upward and gravity pulls her downward. In the figures, we see that the vectors representing rope tensions and weight balance out. $\Sigma F = 0$, and she is in equilibrium.



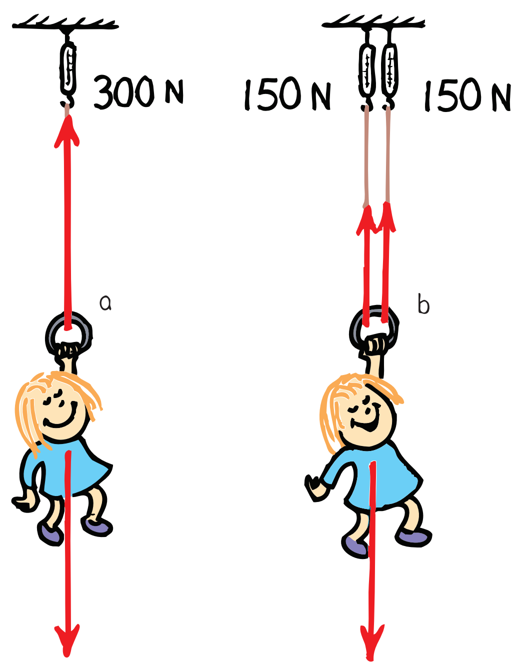


FIGURE 2.9
a. The tension in the rope is 300 N, equal to Nellie's weight.
b. The tension in each rope is now 150 N, half of Nellie's weight. In each case, $\Sigma F = 0$.

CONCEPT CHECK Objects at rest are said to be in static equilibrium; objects moving at constant speed in a straight-line path are said to be in dynamic equilibrium.

Teaching Resources
- **Reading and Study Workbook**
- **Presentation*EXPRESS***
- **Interactive Textbook**

2.5 Vectors

Key Term
resultant

This is the most challenging part of the chapter. Take your time with the parallelogram rule. When you draw the parallelograms, take care to draw opposite sides parallel. Graphic art types will learn this easily, but those without an eye for graphics may be seriously challenged. Again, the Concept-Development Practice Book offers several ramps to understanding.

PAUL

If you want to cover vectors extensively, continue to Appendix D and demonstrate a sailboat sailing into the wind. This is a fascinating and powerful demonstration of vector resolution. Do this with a sailcart, preferably on an air track.

PAUL

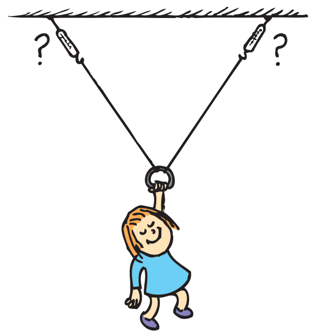
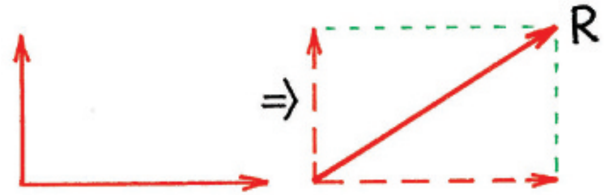


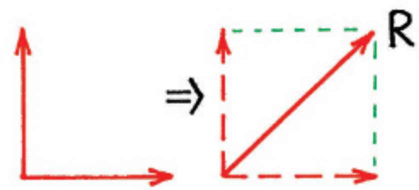
FIGURE 2.10 ▲
When the ropes are at an angle to each other, you need to use the parallelogram rule to determine their tension.

Combining vectors is quite simple when they are parallel. If they are in the same direction, they add. If they are in opposite directions, they subtract. The sum of two or more vectors is called their **resultant.** But what about vectors that act at an angle to each other? Consider Nellie hanging by a pair of ropes, as shown in Figure 2.10. To find the resultant of nonparallel vectors, we use the parallelogram rule.[2.5]

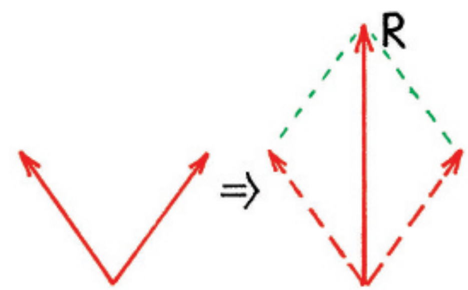
The Parallelogram Rule **To find the resultant of two nonparallel vectors, construct a parallelogram wherein the two vectors are adjacent sides. The diagonal of the parallelogram shows the resultant.** Consider two vectors at right angles to each other, as shown below. The constructed parallelogram in this special case is a rectangle. The diagonal is the resultant *R*.



In the special case of two perpendicular vectors that are equal in magnitude, the parallelogram is a square. Since for any square the length of a diagonal is $\sqrt{2}$, or 1.414, times one of the sides, the resultant is $\sqrt{2}$ times one of the vectors. For example, the resultant of two equal vectors of magnitude 100 acting at a right angle to each other is 141.4.



Now consider the vectors shown below, which represent the tensions of the ropes in Figure 2.10. Notice that the tension vectors form a parallelogram in which the resultant *R* is vertical.



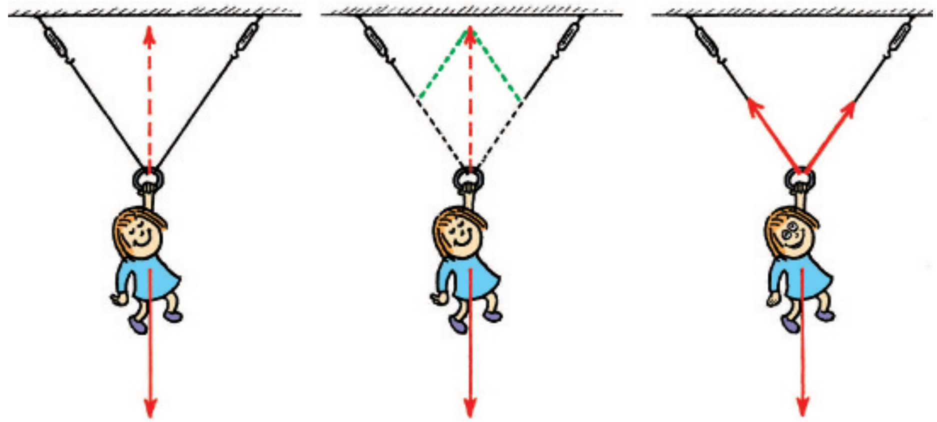
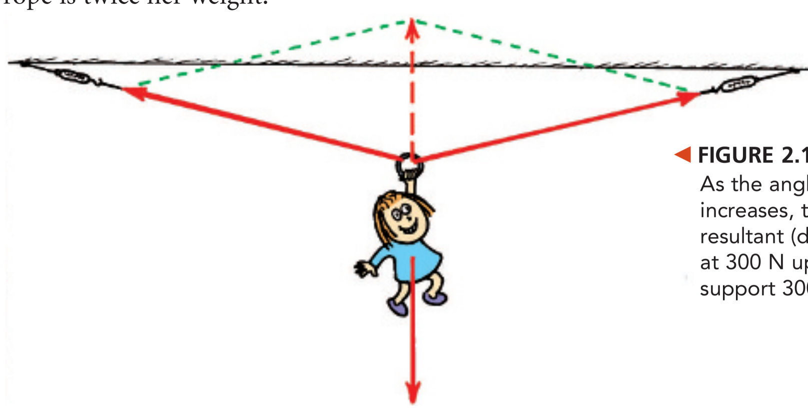


FIGURE 2.11 ▲
a. Nellie's weight is shown by the downward vertical vector. An equal and opposite vector is needed for equilibrium, shown by the dashed vector. **b.** This dashed vector is the diagonal of the parallelogram defined by the dotted lines. **c.** Both rope tensions are shown by the constructed vectors.

Applying the Parallelogram Rule When Nellie Newton is suspended at rest from the two non-vertical ropes shown in Figure 2.10, is the rope tension greater or less than tension in the vertical ropes? Note there are three forces acting on Nellie: a tension in the left rope, a tension in the right rope, and her weight. Figure 2.11 shows a step-by-step solution. Because Nellie is suspended in equilibrium, the resultant of rope tensions must have the same magnitude as her weight. Using the parallelogram rule, we find that the tension in each rope is more than half her weight.

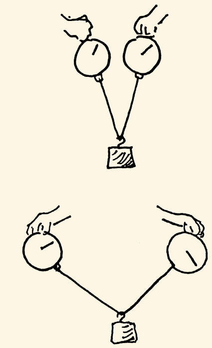
In Figure 2.12, the ropes are at a greater angle from the vertical. Note that the tensions in both ropes are appreciably greater. As the angle between the supporting ropes increases, the tension increases. In terms of the parallelogram, as the angle increases, the vector lengths increase in order for the diagonal to remain the same. Remember, the upward diagonal must be equal and opposite to Nellie's weight. If it isn't, she won't be in equilibrium. By measuring the vectors, you'll see that for this particular angle the tension in each rope is twice her weight.



◀ **FIGURE 2.12**
As the angle between the ropes increases, tension increases so that the resultant (dashed-line vector) remains at 300 N upward, which is required to support 300-N Nellie.

Demonstration

Set up a pair of scales that support a heavy weight as shown (a 1-kg mass is fine). Show that as the supporting angle increases, the tension also increases.



▶ **Teaching Tip** If you don't use a pair of scales, have some students tie a string to each of their forefingers and suspend a weight from the middle. When the strings are vertical, half the weight is felt in each finger. String tension is then half *mg*. Ask how the tension varies as fingers are brought apart so a greater angle exists between each string.

▶ **Teaching Tip** Explain why the tension increases with increasing angle—that the resultant of tensions in each strand must combine to a vector equal and opposite of the weight vector.

▶ **Teaching Tip** Revisit the Discover! activity on page 12. Point out that it is impossible to make a rope perfectly straight by pulling on its ends. Since all ropes have weight, it is necessary that there be an upward component of the tension to balance the downward pull of gravity.

Teaching Tip Here's a nice example to pose to students: Nobody can break a guitar string by pulling on its ends. But if it is strung tightly on a guitar, a slight force to the side easily snaps it.

Teaching Tip The parallelogram rule is useful knowledge for pre-trig or post-trig students.

CONCEPT CHECK To find the resultant of two vectors, construct a parallelogram wherein the two vectors are adjacent sides. The diagonal of the parallelogram shows the resultant.

Teaching Resources

- **Reading and Study Workbook**
- **Concept-Development Practice Book** *2-2*
- **Problem-Solving Exercises in Physics** *1-1*
- **Laboratory Manual** *3, 4, 5*
- **Transparency** *2*
- **Presentation*EXPRESS***
- **Interactive Textbook**
- **Next-Time Question** *2-2*

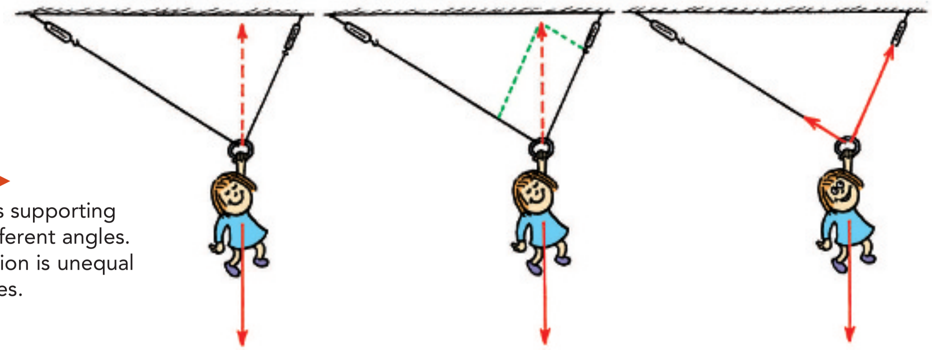


FIGURE 2.13 Here the ropes supporting Nellie have different angles. Note that tension is unequal in the two ropes.

In Figure 2.13, we see Nellie hanging by ropes at different angles from the vertical. Which rope has the greater tension? By the parallelogram rule, we see that the right rope bears most of the load and has the greater tension.

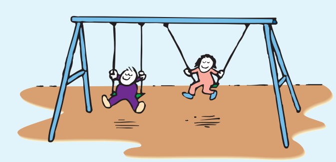
FIGURE 2.14 You can safely hang from a clothesline hanging vertically, but you'll break the clothesline if it is strung horizontally.

If you understand this physics, you will understand why a vertical clothesline can support your weight while a horizontal clothesline cannot. The tension in the horizontal clothesline is much greater than the tension in the vertical clothesline, and so the horizontal one breaks.

CONCEPT CHECK **How can you find the resultant of two vectors?**

think!

Two sets of swings are shown at right. If the children on the swings are of equal weights, the ropes of which swing are more likely to break?
Answer: 2.5.1



Consider what would happen if you suspended a 10-N object midway along a very tight, horizontally stretched guitar string. Is it possible for the string to remain horizontal without a slight sag at the point of suspension?
Answer: 2.5.2

2 REVIEW

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Visit: PHSchool.com
Web Code: csa – 0200

Concept Summary

- A force is needed to change an object's state of motion.
- You can express the equilibrium rule mathematically as $\Sigma F = 0$.
- For an object at rest on a horizontal surface, the support force must equal the object's weight.
- Objects at rest are said to be in static equilibrium; objects moving at constant speed in a straight-line path are said to be in dynamic equilibrium.
- To find the resultant of two nonparallel vectors, construct a parallelogram wherein the two vectors are adjacent sides. The diagonal of the parallelogram shows the resultant.

Key Terms

force *(p. 13)*
net force *(p. 13)*
vector *(p. 14)*
vector quantity *(p. 14)*
scalar quantity *(p. 14)*
mechanical equilibrium *(p. 16)*
equilibrium rule *(p.16)*
support force *(p. 17)*
resultant *(p. 20)*

think! Answers

2.2 In the first case, the reading on each scale will be half her weight. In the second case, when more of her weight is supported by the left ring, the reading on the right reduces to less than half her weight. But in both cases, the sum of the scale readings equals her weight.

2.3.1 Zero, as the scale is at rest. The scale reads the support force (which has the same magnitude as weight), not the net force.

2.3.2 In the first case, the reading on each scale is half your weight. (The sum of the scale readings balances your weight, and the net force on you is zero.) In the second case, if you lean more on one scale than the other, more than half your weight will be read on that scale but less than half on the other. In this way they add up to your weight.

2.4 Neither, for both forces have the same strength. Call the thrust *positive*. Then the air resistance is *negative*. Since the plane is in equilibrium, the two forces combine to equal zero.

2.5.1 The tension is greater in the ropes hanging at an angle. The angled ropes are more likely to break than the vertical ropes.

2.5.2 No way! If the 10-N load is to hang in equilibrium, there must be a supporting 10-N upward resultant. The tension in each half of the guitar string must form a parallelogram with a vertically upward 10-N resultant. For a slight sag, the sides of the parallelogram are very, very long and the tension force is very large. To approach no sag is to approach an infinite tension.

2 REVIEW

▶ **Teaching Tip** How much work to assign to your students? At least enough to keep them engaged. But not so much as to overload them and make your course a chore. The *Check Concepts* problems are a review of student reading, and answers can be picked from the chapter. All students should be successful with *Check Concepts*. Critical thinking, rather than recall, is called for in the *Think and Rank* problems (a new feature in this edition). Likewise with the *Think and Explain* and *Think and Solve* problems.

Teaching Resources
- Teacher*EXPRESS*
- Virtual Physics Lab *1*

2 ASSESS

Check Concepts

1. Force is a push or a pull; net force is the combination of all acting forces.
2. Net force is 10 N to the right.
3. Tension
4. Magnitude and direction
5. Vector quantity needs both magnitude and direction for its description. Scalar quantity is described by magnitude only, a number.
6. Force is a vector quantity; time, area, and volume are scalar quantities.
7. 20 N
8. It means that the vector sum of all the forces that act on an object in equilibrium equal zero.
9. Zero, as the rule $\Sigma F = 0$ states
10. Each arm supports half your weight.
11. 90°; support force is perpendicular (normal) to the surface.
12. Your downward push due to gravity and the upward force of the floor
13. The sum of the readings will equal your weight when you are at rest
14. Yes—if it moves at constant speed in a straight line. Then $\Sigma F = 0$.
15. Both forces are equal in magnitude, but in opposite directions. Thus, the net force is zero.
16. Objects at rest are in static equilibrium; objects moving at constant speed in a straight-line path are in dynamic equilibrium.

2 ASSESS

Check Concepts

Section 2.1

1. What is the difference between force and net force on an object?
2. What is the net force on a box that is being pulled to the right with a force of 40 N and pulled to the left with a force of 30 N?
3. What name is given to the stretching force that occurs in a spring or rope being pulled?
4. What two quantities are necessary to determine a vector quantity?
5. How does a vector quantity differ from a scalar quantity?
6. Give an example of a vector quantity. Give an example of a scalar quantity.

Section 2.2

7. How much tension is in a rope that holds up a 20-N bag of apples at rest?
8. What does $\Sigma F = 0$ mean?
9. What is the net force on an object at rest?
10. When you do pull-ups and you hang at rest, how much of your weight is supported by each arm?

Section 2.3

11. What is the angle between a support force and the surface on object rests upon?
12. What two forces compress a spring inside a weighing scale when you weigh yourself?
13. When you are at rest and supported by a pair of weighing scales, how does the sum of the scale readings compare with your weight?

Section 2.4

14. Can an object be moving and still be in equilibrium? Defend your answer.
15. If you push a crate across a factory floor at constant speed in a constant direction, what is the magnitude of the force of friction on the crate compared with your push?
16. Distinguish between static equilibrium and dynamic equilibrium.

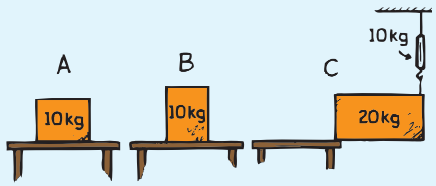
Section 2.5

17. According to the parallelogram rule for two vectors, what does the diagonal of a constructed parallelogram represent?
18. Consider the suspension of Nellie in Figure 2.11. Name the three forces that act on her. What is your evidence that they cancel to zero?
19. Consider Nellie in Figure 2.12. What changes in rope tension occur when the ropes make a greater angle with the vertical?
20. When Nellie hangs from ropes at different angles, as shown in Figure 2.13, how does the vector resultant of the two rope tensions compare with her weight?

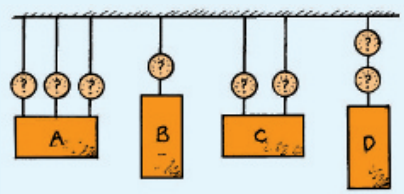
Think and Rank

Rank each of the following sets of scenarios in order of the quantity or property involved. List them from left to right. If scenarios have equal rankings, then separate them with an equal sign. (e.g., A = B)

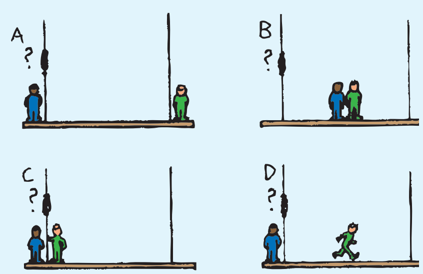
21. Blocks A and B are supported by the table. Block C is partly supported by the table and partly by the rope. Rank the support forces provided by the table from greatest to least.



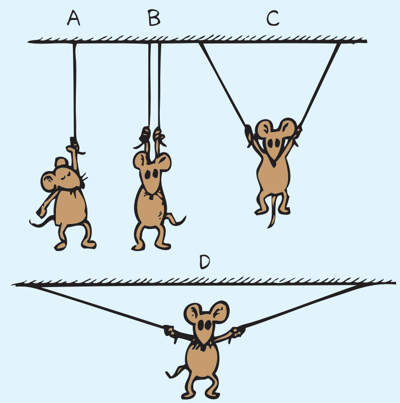
22. In the diagram below, identical blocks are suspended by ropes, each rope having a scale to measure the tension (stretching force) in the rope. Rank the scale readings from greatest to least.



23. Burl and Paul stand on their sign-painting scaffold. Tension in the left rope is measured by a scale. Rank the tensions in that rope from greatest to least.



24. Percy does gymnastics, suspended by one rope in A and by two ropes in positions B, C, and D. Rank the tensions in the ropes from greatest to least.



Think and Explain

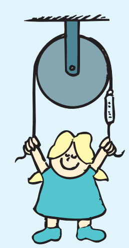
25. A cat lies on the floor. Can you say that no force acts on the cat? Or is it correct to say that no *net* force acts on the cat? Explain.

26. Consider two forces, one having a magnitude of 20 N and the other a magnitude of 12 N. What is the maximum net force possible for these two forces? The minimum ?

27. When a box of chocolate bars is in mechanical equilibrium, what can be correctly said about all the forces that act on it? Must the net force necessarily be zero?

28. Faina says that an object cannot be in mechanical equilibrium when only a single force acts on it. Do you agree or disagree?

29. Phyllis Physics hangs at rest from the ends of the rope, as shown at right. How does the reading on the scale compare to her weight?



17. The diagonal is the resultant, or the sum of the two vectors.

18. Downward force is weight. Two upward forces are tensions in ropes. Being at rest (in equilibrium) is evidence that $\Sigma F = 0$.

19. Rope tensions increase.

20. Resultant of both rope tensions is equal in magnitude and opposite in direction to the vector representing her weight.

Think and Rank

21. A = B = C

22. B = D, C, A

23. C, D, A = B

24. D, A, C, B

Think and Explain

25. Correct to say no net force, as both gravity and support of the floor act on cat.

26. Maximum resultant occurs when forces are parallel in same direction: 32 N. The minimum occurs when they oppose each other: 8 N.

27. The sum of all forces (i.e., the net force) must equal zero. Yes; in mechanical equilibrium, $\Sigma F = 0$.

28. Agree; if only a single nonzero force acts on an object, it will not be in mechanical equilibrium. There must be one or more additional forces to produce zero net force for equilibrium.

29. Scale reads half her weight. So, ΣF = upward pull of left rope + upward pull of right rope − weight = 0.

30. At left, Harry is supported by two strands of rope that share his weight (like Phyllis in Question 29). So each strand supports 250 N, below the breaking point. At right, Harry is supported by just one strand, which requires tension of 500 N. This is above the breaking point of the rope, which breaks and changes his vacation plans.

31. Two forces—weight and support force

32. The book doesn't rise because the net force on it is zero: weight − support force = 0.

33. No; the reading is the same. Pressure against the scale is less on one foot, but not the weight.

34. Yes, it is in dynamic equilibrium; it is not undergoing a change in its motion.

35. 200 N; constant speed in a straight line, so $\Sigma F = 0 =$ force of pulling − friction.

36. Support force on the refrigerator decreases as it's lifted. When entirely lifted from the floor, the support force provided by the floor is zero, and the support force on the men's feet increases as the load transfers from the floor to them.

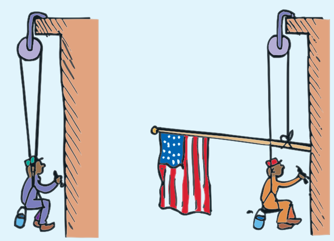
37. If perfectly vertical, then tension in each wire is half of Sneezlee's weight. But the wires are only nearly vertical, so tension in each is greater than half the weight.

38. Greater tension, as a parallelogram would show. (Interestingly, a 60° angle results in tension equal to the weight. If angle exceeds 60°, tension in the wire exceeds the weight.)

39. Tension in each wire is greater than half the weight of the picture.

2 ASSESS *(continued)*

30. Harry the painter swings year after year from his bosun's chair. His weight is 500 N and the rope, unknown to him, has a breaking point of 300 N. Why doesn't the rope break when he is supported as shown at the left? One day Harry is painting near a flagpole, and, for a change, he ties the free end of the rope to the flagpole instead of to his chair as shown at the right. Why did Harry end up taking his vacation early?



31. How many significant forces act on a your physics book when it is at rest on a table? Identify the forces.

32. Why doesn't the support force that acts on a book resting on a table cause the book to rise from the table?

33. Nicole stands on a bathroom scale and reads her weight. Does the reading change if she stands on one foot instead of both feet? Defend your answer.

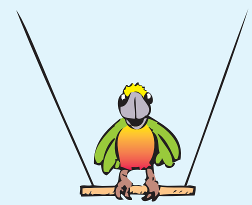
34. Justin sets a hockey puck sliding across the ice at a constant speed. Is the puck in equilibrium? Why or why not?

35. Alyssa pulls horizontally on a crate with a force of 200 N, and it slides across the floor at a constant speed in a straight line. How much friction is acting on the crate?

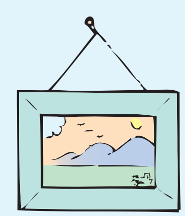
36. Consider a heavy refrigerator at rest on a kitchen floor. When Anthony and Daniel start to lift it, does the support force on the refrigerator provided by the floor increase, decrease, or remain unchanged? What happens to the support force on Anthony's and Daniel's feet?

37. Sneezlee is supported by two thin wires. Is the tension in each wire less than, equal to, or more than half his weight? Use the parallelogram rule to defend your answer.

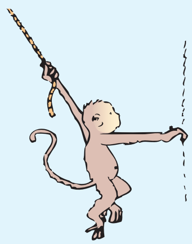
38. Sneezlee's wire supports are repositioned as shown. How does the tension in each wire compare with the tension of the previous question?



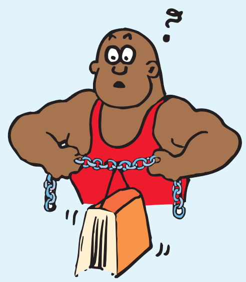
39. If a picture frame were supported by a pair of vertical wires, tension in each wire would be half the weight of the frame. When the frame is supported by wires at an angle, as shown below, how does the tension in each wire compare with that of vertical wires?



40. A monkey hangs by a strand of rope and holds onto the zoo cage as shown. Since her arm holding the cage is horizontal, only the rope supports her weight. How does the tension in the rope compare with her weight?



41. Why can't the strong man pull hard enough to make the chain perfectly straight?



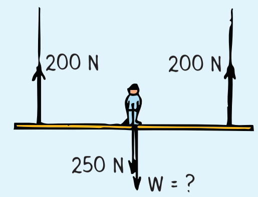
Think and Solve

42. Two vertical chains are used to hold up a 1000-N log. One chain has a tension of 400 N. Find the tension in the other chain.

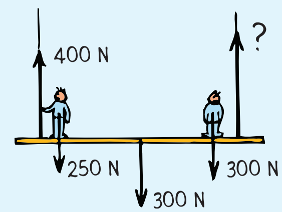
43. Lucy Lightweight stands with one foot on one bathroom scale and her other foot on a second bathroom scale. Each scale reads 300 N. What is Lucy's weight?

44. Harry Heavyweight, who weighs 1200 N, stands on a pair of bathroom scales so that one scale reads twice as much as the other. What are the scale readings?

45. The sketch shows a painter's staging in mechanical equilibrium. The person in the middle weighs 250 N, and the tensions in both ropes are 200 N. What is the weight of the staging?



47. A staging that weighs 300 N supports two painters, one 250 N and the other 300 N. The reading in the left scale is 400 N. What is the reading in the right scale?



47. Two children push on a heavy crate that rests on a basement floor. One pushes horizontally with a force of 150 N and the other pushes in the same direction with a force of 180 N. The crate remains stationary. Show that the force of friction between the crate and the floor is 330 N.

48. Two children push on a crate. They find that when they push together horizontally with forces of 155 N and 187 N, respectively, the crate slides across the floor at a constant speed. Show that the force of friction between the crate and the floor is 342 N.

More Problem-Solving Practice
Appendix F

40. Tension in the rope is greater than her weight.

41. Chain tensions on both sides of the book must form a parallelogram with a resultant that equals the weight of the book. This can only occur if each side of the chain makes an angle to the horizontal.

Think and Solve

42. From $\Sigma F = 0$, total upward tensions = weight of log. 400 N + tension in other chain = 1000 N. Tension in other chain = 1000 N − 400 N = 600 N.

43. If each scale reads 300 N, Lucy's total weight = 600 N.

44. 800 N on one, 400 N on the other

45. $\Sigma F = 0$, upward forces are 400 N, and downward forces are 250 N + weight of staging. So staging weighs 150 N.

46. $\Sigma F = 0$, upward forces are 400 N + tension in right scale, and downward forces are 250 N + 300 N + 300 N = 850 N. Reading on the right scale is 450 N.

47. From $\Sigma F = 0$, Σforces in one direction = Σforces in opposite direction. So, 150 N + 180 N = force of friction = 330 N in opposite direction to the children's pushes.

48. Crate moves at constant speed in a straight line, so $\Sigma F = 0$. Σforces in one direction = Σforces in opposite direction. So, 155 N + 187 N = force of friction = 342 N in opposite direction to the children's pushes.

Teaching Resources

- **Computer Test Bank**
- **Chapter and Unit Tests**