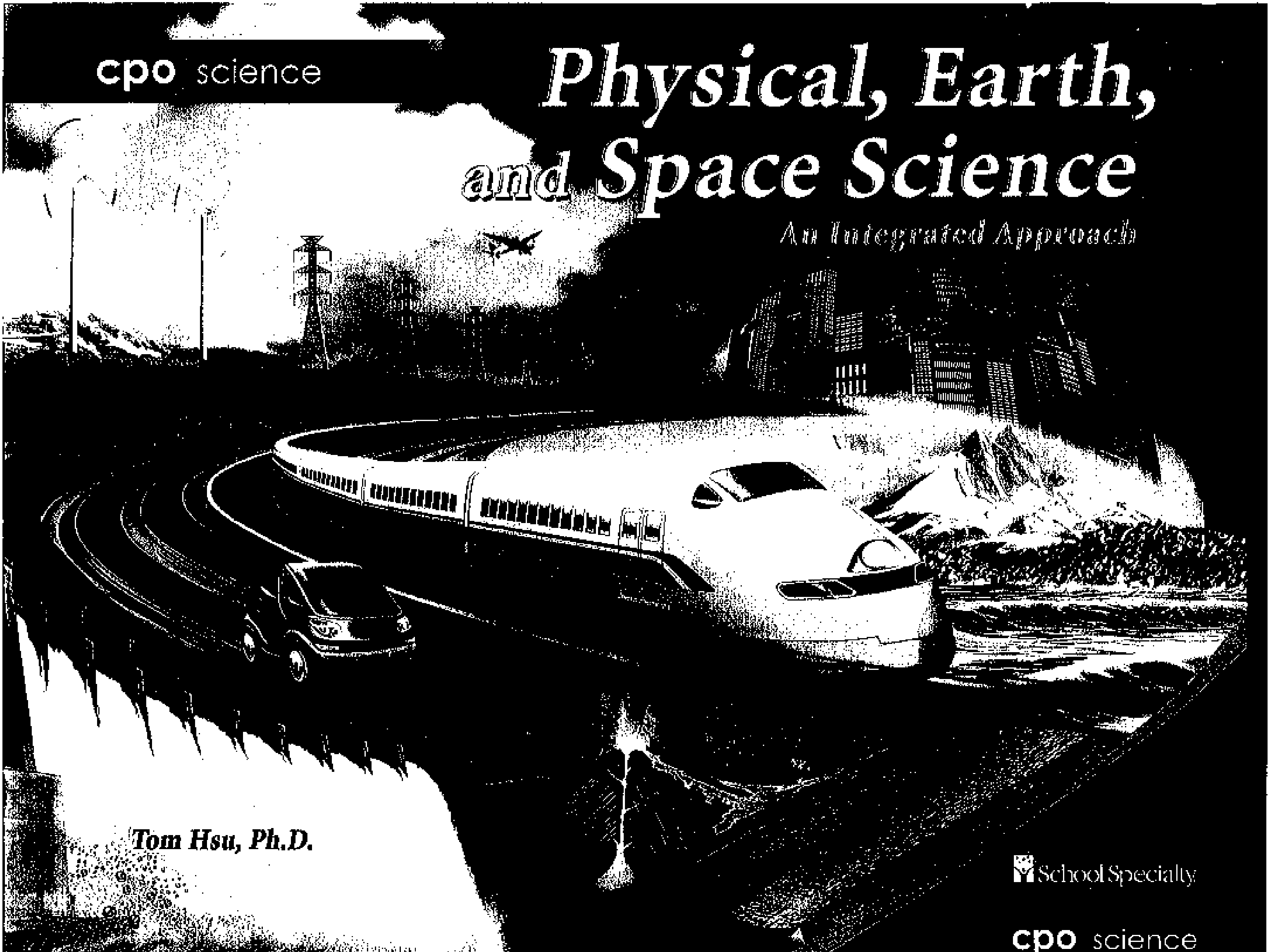
cpo science

Physical, Earth, and Space Science

An Integrated Approach



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School Specialty

cpo science

Chapter 4
Motion

How long can you stand perfectly still? Ten seconds? A minute? Even if you stand still, things inside your body, such as your heart and lungs, are moving. Even when you are fast asleep your body is not really at rest.

The 24-hour rotation of Earth is carrying you around at several hundred miles per hour. Every 365 days, Earth completes a 584-million-mile orbit around the Sun. To make this trip, Earth (with you on its surface) is rushing through space at the astounding speed of 67,000 miles per hour! In order to understand nature, we need to think about motion. How do we describe going from here to there? The ideas in this chapter apply to all motion, whether it is a toy car rolling along a track or Earth rushing through space. Position, speed, and acceleration are basic concepts of motion we need to understand in order to understand the physical world. We will explore these concepts, and more, in this chapter.

Key Questions

✔ *How do we accurately describe our position?*

✔ *How do we show motion on a graph?*

✔ *What is special about the motion of falling objects?*

Photo courtesy of NASA

4.1 Speed and Velocity

The term **speed** describes how quickly something moves. In this section, you will learn about speed and speed with direction, called velocity.

Speed

Calculating speed

To calculate the speed of a moving object, you divide the distance the object moves by the time it takes to move. For example, if you drive 120 miles (the distance) and it takes you 2 hours (the time), your speed is 60 miles per hour (60 mph = 120 miles ÷ 2 hours). The lowercase letter v is used to represent speed, as shown in the formula below.

SPEED

$$\text{Speed (cm/s)}\; v = \frac{d}{t} \quad \begin{matrix}\text{Distance (cm)} \\ \text{Time (s)}\end{matrix}$$

Units for speed

The units for speed are distance units over time units. If distance is in kilometers and time is in hours, then speed is in kilometers per hour (km/h). Other SI units for speed are cm per second (cm/s) and meters per second (m/s). Your family's car probably shows speed in miles per hour (mph).

Average speed and instantaneous speed

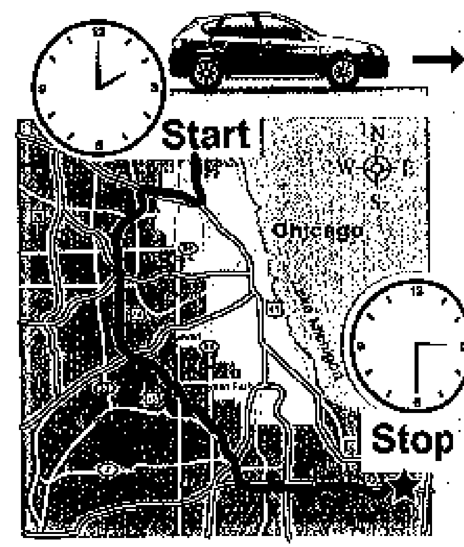
When you divide the total distance of a trip by the time taken, you get the **average speed**. Figure 4.1 shows an average speed of 100 km/h. But think about what happens when you are riding in a car. On a real trip, your car will slow down and speed up. Sometimes your speed will be higher than 100 km/h, and sometimes lower (even 0 km/h). The speedometer shows you the car's **instantaneous speed**. The instantaneous speed is the *actual* speed an object has at any moment.

VOCABULARY

speed - describes how quickly an object moves, calculated by dividing the distance traveled by the time it takes.

average speed - the total distance divided by the total time for a trip.

instantaneous speed - the actual speed of a moving object at any moment.



$$\frac{\text{150 kilometers}}{\text{1.5 hours}} = \text{100 kilometers (km/h)}$$

Figure 4.1: *A driving trip with an average speed of 100 km/h.*

Solving Problems: Speed

How far will you go if you drive for 2 hours at a speed of 100 km/h?

1. **Looking for:** You are asked for a distance.
2. **Given:** You are given the speed and the time.
3. **Relationships:** speed = distance ÷ time

   distance = speed × time
4. **Solution:** distance = (100 km/h) × (2 h) = 200 km

Your turn...

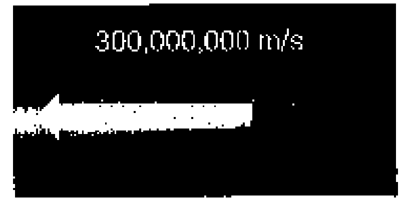
a. You travel at an average speed of 20 km/h in a straight line to get to your grandmother's house. It takes you 3 hours to get to her house. How far away is her house from where you started?

b. What is the speed of a snake that moves 20 meters in 5 seconds?

c. A train is moving at a speed of 50 km/h. How many hours will it take the train to travel 600 kilometers?

SCIENCE FACT

The Speed Limit of the Universe



The fastest speed in the universe is the speed of light. Light moves at approximately 300 million meters per second (3×10^8 m/s). If you could make light travel in a circle, it would go around the Earth 7.5 times in one second! Scientists believe the speed of light is the ultimate speed limit in the universe.

SOLVE FIRST LOOK LATER

a. Your grandmother's house is 60 km away from where you started.

b. The snake's speed is 4 m/s.

c. It will take the train 12 hours to travel 600 kilometers.

Velocity

What is velocity? Recall that *position* is an example of a kind of variable called a *vector*. We use the term **velocity** to mean speed with direction. Velocity (Figure 4.2) is usually defined as positive when moving forward (to the right from an outside observer), and negative when moving backward (to the left to an outside observer).

The difference between velocity and speed Velocity is a vector, speed is not. In regular conversation, you might use the two words to mean the same thing. In science, they are related but different. Speed can have only a positive value (or zero) that tells you how far you move per unit of time (like meters per second). Velocity is speed *and* direction. If the motion is in a straight line, the direction can be shown with a positive or negative sign. The sign tells the direction and the quantity (speed) tells you how quickly you are moving.

Use two variables to find the third one Any formula that involves speed can also be used for velocity. For example, you move 2 meters if your *speed* is 0.2 m/s and you keep going for 10 seconds. But did you move forward or backward? You move −2 meters (backward) if you move with a *velocity* of −0.2 m/s for 10 seconds. Using the formula with velocity gives you the change of *position* instead of *distance*.

Word Formulas		Equation
speed = distance ÷ time	velocity = distance ÷ time	$v = \frac{d}{t}$
distance = speed × time	distance = velocity × time	$d = vt$
time = distance ÷ speed	time = distance ÷ velocity	$t = \frac{d}{v}$

Direction of movement Suppose an object moves forward at 0.2 m/s for 10 seconds. Its velocity is +0.2 m/s. In 10 seconds, its position changes by +2 meters.

Now, suppose the object goes backward at 0.2 m/s for 4 seconds. This time the velocity is −0.2 m/s. The change in position is −0.8 meters. *A change in position is velocity × time* (Figure 4.3).

VOCABULARY

velocity - a variable that tells you both speed and direction.

Velocity is speed and direction.

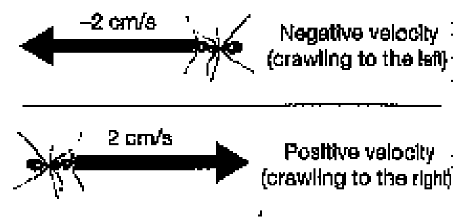


Figure 4.2: *Velocity can be a positive or a negative value.*

FORMULA

Change in position = Velocity × Time

= 0.2 m/s × 10 seconds

= +2 meters

Figure 4.3: *The change in position or distance is the velocity multiplied by the time.*

Solving Problems: Velocity

A train travels at 100 km/h heading east to reach a town in 4 hours. The train then reverses and heads west at 50 km/h for 4 hours. What is the train's position now?

1. **Looking for:** You are asked for position.
2. **Given:** You are given two velocity vectors and the times for each.
3. **Relationships:** change in position = velocity × time
4. **Solution:** The first change in position is (+100 km/h) × (4 h) = +400 km
   The second change in position is (–50 km/h) × (4 h) = –200 km
   The final position is (+400 km) + (–200 km) = +200 km. The train is 200 km east of where it started.

Your turn...

a. A car travels south on a highway for 2 h at 90 km/h. The car reverses direction and heads north for 0.5 h at 80 km/h. What is the car's position relative to where it started?

b. A ship needs to sail to an island that is 1,000 km south of where the ship starts. If the captain sails south at a steady velocity of 30 km/h for 30 h, will the ship make it?

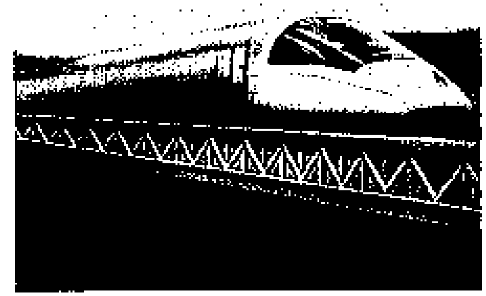
SCIENCE FACT

Fast Trains!

The bullet train of Japan was the world's first high-speed train. When it came into use in 1964, it went 210 km/h.

Research today's high-speed trains of the world. How fast can they go?

Research to find out why the United States lags behind in having high-speed trains. Find out the advantages and disadvantages of having high-speed trains in the U.S.



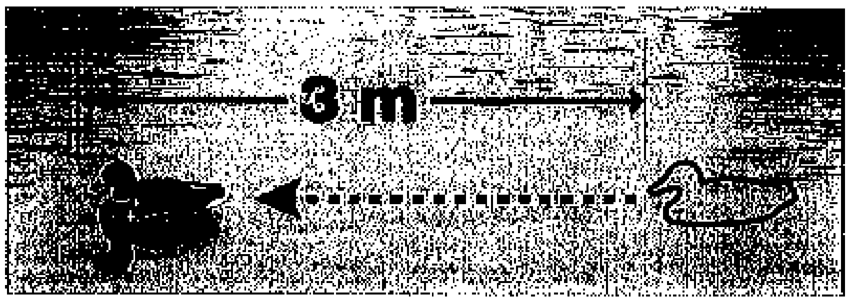
SOLVE FIRST—LOOK LATER

a. The car is 140 km south of where it started.

b. No, because
30 km/h × 30 h = 900 km.
The island is still 100 km away.

Section 4.1 Review

1. What is your average speed if you walk 2 kilometers in 20 minutes?
2. Give an example where instantaneous speed is different from average speed.
3. A weather report says winds blow at 5 km/h from the northeast. Is this description of the wind a speed or velocity? Explain your answer.
4. What velocity vector will move you 200 miles east in 4 hours traveling at a constant speed?
5. Explain how a bicycle can be fast compared to walking and slow compared to driving. How can two opposite words (*fast* and *slow*) describe the same speed?
6. What is the speed of the duck in the picture below if it takes 15 seconds to move the distance shown?

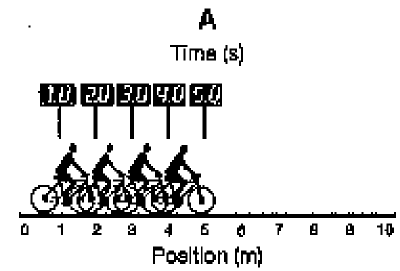


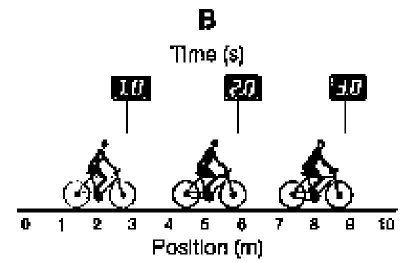
7. Can you go 500 kilometers in 8 hours without driving faster than 55 mph? Explain your answer.
8. A boat sails an average speed of 20 km/h for 2 days. How far does the boat travel?
9. What is the difference between speed and velocity?
10. A bird flies west for 1 hour at a velocity of 15 km/hr. The bird switches direction and flies east for 1 hour at a velocity of 10 km/hr. What is the bird's position relative to where it started?

CHALLENGE

Look at the graphic below and answer the following questions.

1. How fast is each cyclist going in units of meters per second*?
2. Which cyclist is going faster? How much faster is this cyclist going compared to the other one?





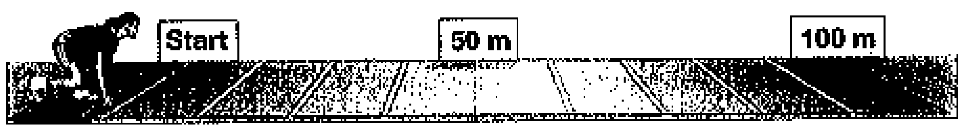
*The word *per* means "for every" or "for each." Saying "5 kilometers per hour" is the same as saying "5 kilometers for each hour." You can also think of *per* as meaning "divided by." The quantity before the word *per* is divided by the quantity after it.

4.2 Graphs of Motion

Consider the phrase "a picture is worth a thousand words." A graph is a special kind of picture that can quickly give meaning to a lot of data (numbers). You can easily spot relationships on a graph. It is much more difficult to see these same relationships by looking at columns of numbers. Compare the table of numbers to the graph in Figure 4.4 and see if you agree!

The position vs. time graph

Recording data Imagine you are helping a runner who is training for a track meet. She wants to know if she is running at a **constant speed.** Constant speed means the speed stays the same. You mark the track every 50 meters. Then you measure her time at each mark as she runs. The data for your experiment is shown in Figure 4.4. This is position vs. time data because it tells you the runner's position at different points in time. She is at 50 meters after 10 seconds, 100 meters after 20 seconds, and so on.



Graphing data To graph the data, you put position on the vertical (y) axis and time on the horizontal (x) axis. Each row of the data table makes one point on the graph. Notice the graph goes over to the right 10 seconds and up 50 meters between each point. This makes the points fall exactly in a straight line. The straight line tells you the runner moves the same distance during each equal time period. *An object moving at a constant speed always creates a straight line on a position vs. time graph.*

Calculating speed The data shows that the runner took 10 seconds to run each 50-meter segment. Because the time and distance was the same for each segment, you know her speed was the same for each segment. You can use the formula $v = d/t$ to calculate the speed. Dividing 50 meters by 10 seconds tells you her constant speed was 5 meters per second.

VOCABULARY

constant speed - speed that stays the same.

Position and Time Data for a Runner

Time (s)	Position (m)
0	0
10	50
20	100
30	150

Runner's Position vs. Time

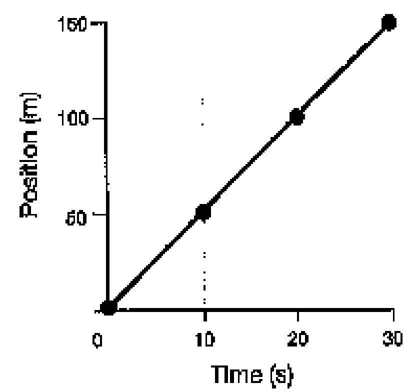


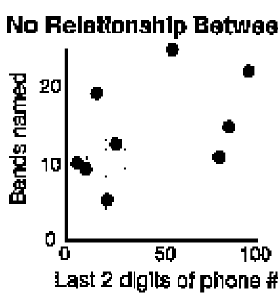
Figure 4.4: *A data table and a position vs. time graph for a runner.*

Graphs show relationships between variables

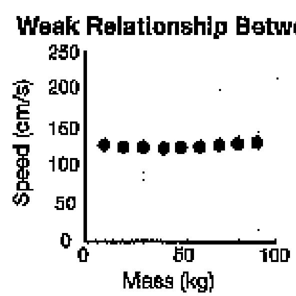
Relationships between variables Think about rolling a toy car down a ramp. You theorize that steeper angles on the ramp will make the car go faster. How do you find out if your theory is correct? You need to know the relationship between the variables *angle* and *speed*.

Patterns on a graph show relationships Recall that in a graph, the dependent variable is usually plotted on the vertical (or y) axis and the independent variable is usually on the horizontal (or x) axis. Each axis is marked with the range of values the variable has. In Figure 4.5, the x-axis (angle) has values between 0 and 60 degrees. The y-axis (average speed) has values between 0 and 300 cm/s. You can tell there is a relationship because all the points on the graph follow the same curve that slopes up and to the right. The graph tells you instantly that the average speed increases as the ramp gets steeper.

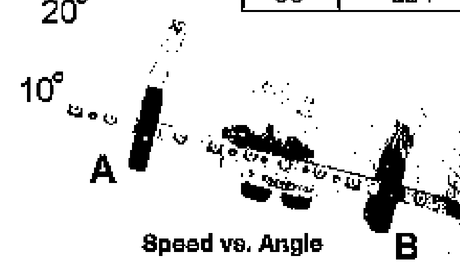
Recognizing a relationship from a graph Recall that the relationship between variables may be strong, weak, or there may be no relationship at all. In a strong relationship, large changes in one variable make similarly large changes in the other variable, like in Figure 4.5. In a weak relationship, large changes in one variable cause only small changes in the other. The graph on the right (below) shows a weak relationship. When there is no relationship, the graph looks like scattered dots (below left). The dots do not make an obvious pattern (a line or curve).



Bands named	Tel. # Ends in
10	08
15	86
19	15
6	22
22	98
9	10
25	63
12	94
11	79



Mass (kg)	Speed (cm/s)
10	128
20	125
30	123
40	122
50	123
60	124
70	126
80	127
90	128



Angle (degrees)	Average Speed (cm/s)
10	106
20	144
30	181
40	205
50	224

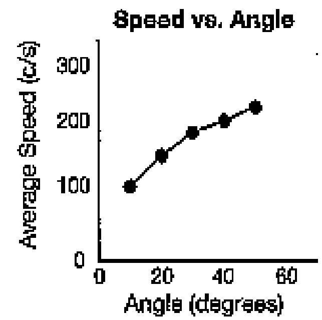
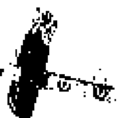


Figure 4.5: *This graph shows that the average speed between A and B increases as the angle of the track increases.*

Average speed (cm/s)
106
144
181
205
224



...ows that ... and B ... track

Slope

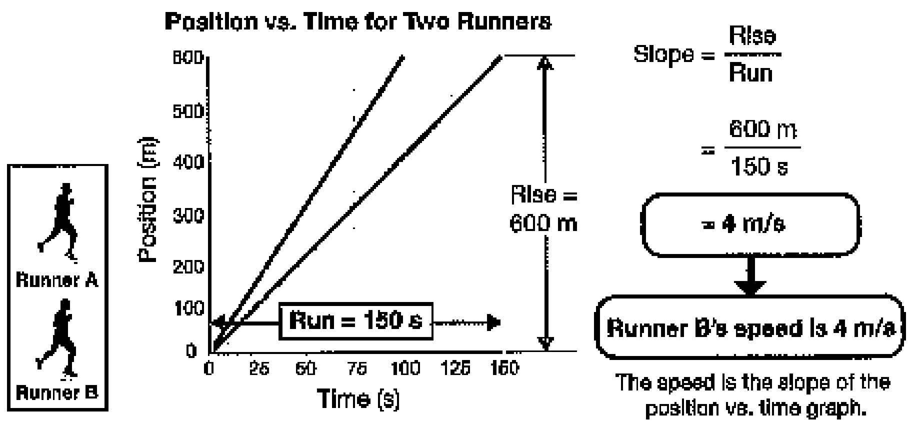
Comparing speeds

You can use position vs. time graphs to quickly compare speeds. Figure 4.6 shows a position vs. time graph for two people running along a jogging path. Both runners start at the beginning of the path (the origin) at the same time. Runner A (blue) takes 100 seconds to run 600 meters. Runner B (red) takes 150 seconds to go the same distance. Runner A's speed is 6 m/s (600 ÷ 100) and runner B's speed is 4 m/s (600 ÷ 150). Notice that the line for runner A is *steeper* than the line for runner B. A steeper line on a position vs. time graph means a faster speed.

A steeper line on a position vs. time graph means a faster speed.

Calculating slope

The "steepness" of a line is called its slope. The **slope** is the ratio of the *rise* (vertical change) divided by the *run* (horizontal change). The diagram below shows how to calculate the slope of a line. Visualize a triangle with the slope as the hypotenuse. The rise is the height of the triangle. The run is the length along the base. Here, the x-axis is time and the y-axis is position. The slope of the graph is therefore the distance traveled divided by the time it takes, or the speed. The units are the units for the rise (meters) divided by the units for the run (seconds), meters per second, or m/s.



VOCABULARY

slope - the ratio of the rise (vertical change) to the run (horizontal change) of a line on a graph.

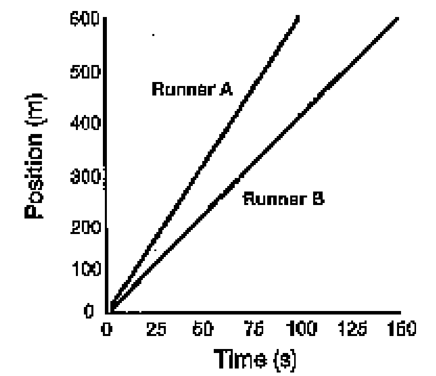


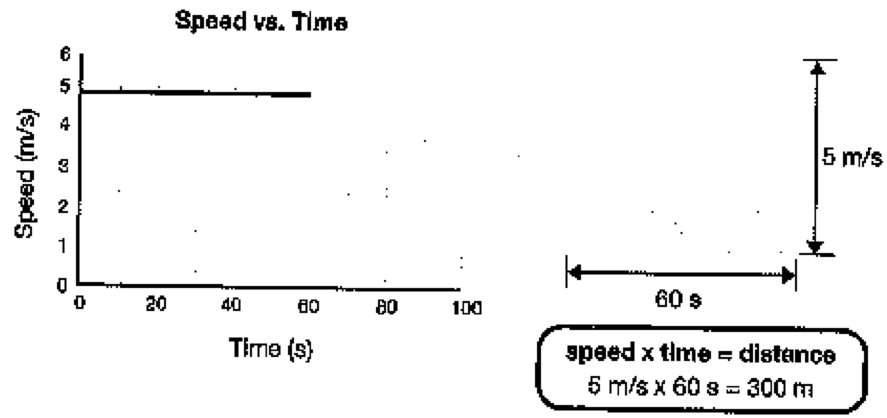
Figure 4.6: *A position vs. time graph for two runners.*

Speed vs. time graphs

Constant speed on a speed vs. time graph The speed vs. time graph has speed on the y-axis and time on the x-axis. The bottom graph in Figure 4.7 shows the speed vs. time for the runner. The top graph shows the position vs. time. Can you see the relationship between the two graphs? The blue runner has a speed of 5 m/s. The speed vs. time graph shows a horizontal line at 5 m/s for the entire time. On a speed vs. time graph, constant speed is shown with a straight horizontal line. At any point in time between 0 and 60 seconds the line tells you the speed is 5 m/s.

Another example The red runner's line on the position vs. time graph has a less steep slope. That means her speed is slower. You can see this immediately on the speed vs. time graph. The red runner shows a line at 4 m/s for the whole time.

Calculating distance A speed vs. time graph can also be used to find the *distance* the object has traveled. Remember, distance is equal to speed multiplied by time. Suppose we draw a rectangle on the speed vs. time graph between the x-axis and the line showing the speed. The area of the rectangle (shown below) is equal to its length times its height. On the graph, the length is equal to the time and the height is equal to the speed. Therefore, the area of the graph is the speed multiplied by the time. This is the distance the runner traveled.



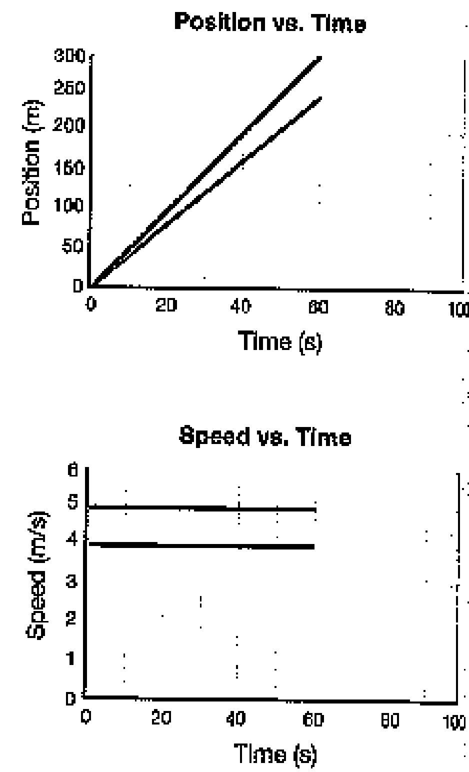
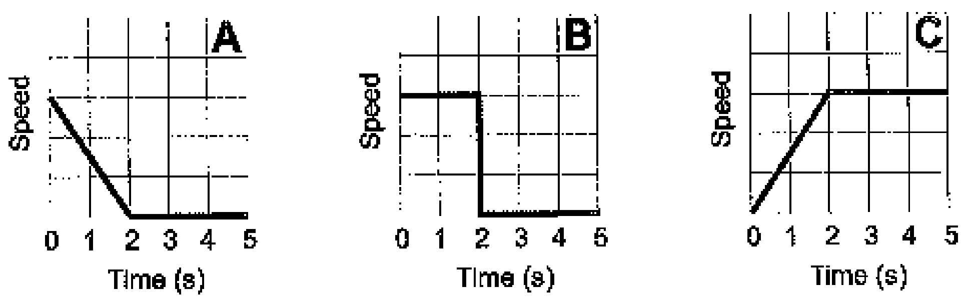


Figure 4.7: *The position vs. time graph (top) shows the exact same motion as the speed vs. time graph (bottom).*

Section 4.2 Review

1. On a graph of position vs. time, what do the x-values represent? What do the y-values represent?
2. Explain why time is an independent variable and position is a dependent variable in a position vs. time graph.
3. What does the slope of the line on a position vs. time graph tell you about an object's speed?
4. The graph in Figure 4.8 shows the position and time for two runners in a race. Who has the faster speed, Robin or Joel? Explain how to answer this question without doing calculations.
5. Calculate the speed of each runner from the graph in Figure 4.8.
6. The runners in Figure 4.8 are racing. Predict which runner will get to the finish line of the race first.
7. Maria walks at a constant speed of 2 m/s for 8 seconds.
   a. Draw a speed vs. time graph for Maria's motion.
   b. How far does she walk?
8. Which of the three graphs below corresponds to the position vs. time graph in Figure 4.9?



9. Between which times is the speed zero for the motion shown on the position vs. time graph in Figure 4.9?

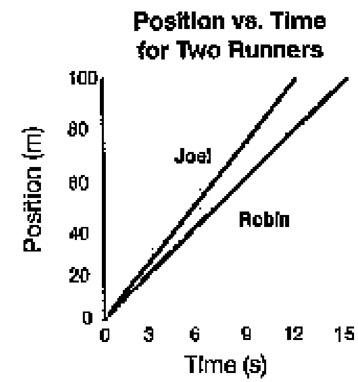


Figure 4.8: *Questions 4, 5, and 6.*

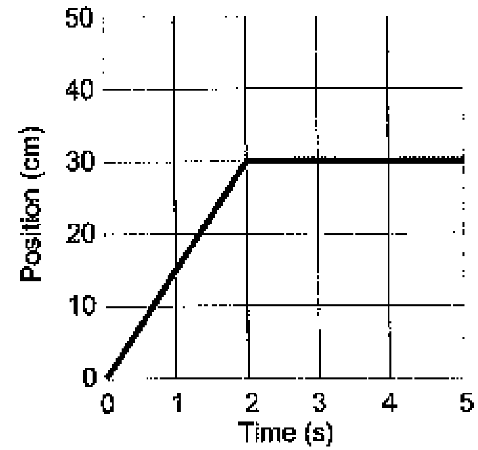


Figure 4.9: *Questions 8 and 9.*

4.3 Acceleration

Constant speed is easy to understand. However, almost nothing moves with constant speed for long. When a driver steps on the gas pedal, the speed of the car increases. When the driver brakes, the speed decreases. Even while using cruise control, the speed goes up and down as the car's engine adjusts for hills. Another important concept in physics is acceleration. Acceleration is how we describe changes in speed or velocity.

An example of acceleration

Definition of acceleration

What happens if you coast down a long hill on a bicycle? At the top of the hill, you move slowly. As you go down the hill, you move faster and faster—you accelerate. **Acceleration** is the rate at which your speed (or velocity) changes. If your speed increases by 1 meter per second (m/s) each second, then your acceleration is 1 m/s per second.

Time (s)	Speed (m/s)
1	1
2	2
3	3
4	4
5	5

Acceleration = 1 m/s each second

Time (s)	Speed (m/s)
1	2
2	4
3	6
4	8
5	10

Acceleration = 2 m/s each second

Acceleration can change

Your acceleration depends on the steepness of the hill. If the hill is a gradual incline, you have a small acceleration, such as 1 m/s per second. If the hill is steeper, your acceleration is greater, perhaps 2 m/s per second.

Acceleration on a speed vs. time graph

Acceleration is easy to spot on a speed vs. time graph. If the speed changes over time then there is acceleration. Acceleration causes the line to slope up on a speed vs. time graph (Figure 4.10). The graph on the top shows constant speed. There is zero acceleration at constant speed because the speed does not change.

VOCABULARY

acceleration - the rate at which velocity changes.

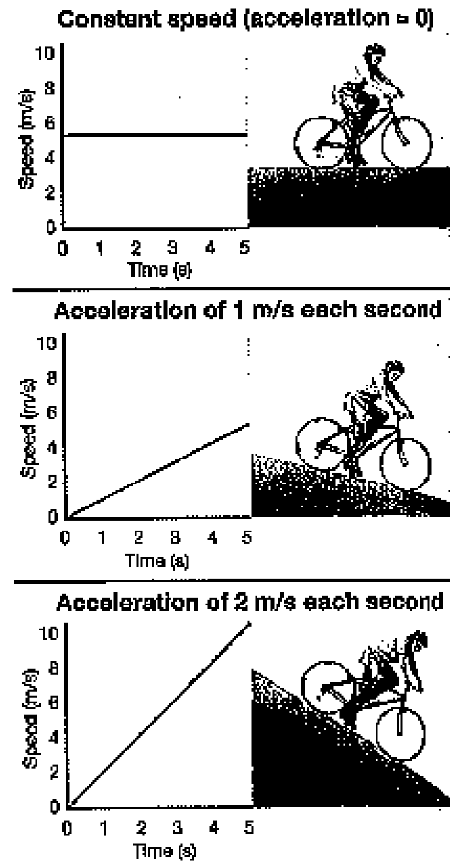


Figure 4.10: *Speed vs. time graphs showing constant speed (top) and acceleration (middle and bottom).*

Speed and acceleration

The difference between speed and acceleration

Speed and acceleration are not the same thing. You can be moving in one direction (nonzero speed) and have no acceleration (think cruise control). But if the brakes are applied and the car slows down, it is accelerating because the speed is now changing (faster to slower).

Example: Acceleration in cars

Acceleration describes how quickly speed changes. More precisely, acceleration is the change in velocity divided by the change in time. For example, suppose a powerful sports car changes its speed from 0 to 60 mph in 5 seconds. In English units, the acceleration is 60 mph ÷ 5 seconds = 12 mph/s. In SI units, 60 mph is about the same as 100 km/h. The acceleration is 100 km/h ÷ 5 seconds, or 20 km/h/s (Figure 4.11). A formula you can use to calculate acceleration is shown below.

ACCELERATION

$$a = \frac{v_{finish} - v_{start}}{t}$$

Acceleration (m/s²): a; Change in velocity (m/s): $v_{finish} - v_{start}$; Time (s): t

Acceleration units

To calculate acceleration, you divide the change in velocity by the amount of time it takes for the change to happen. If the change in speed is in kilometers per hour, and the time is in seconds, then the acceleration is in km/h/s or *kilometers per hour per second.* An acceleration of 20 km/h/s means that the speed increases by 20 km/h *every second.*

What is a meter per second squared?

The time units for acceleration are often written as seconds squared or s^2. For example, acceleration might be 50 meters per second squared or 50 m/s^2. The steps in Figure 4.12 show how to simplify the fraction m/s/s to get m/s^2. Saying *seconds squared* is just a math-shorthand way of speaking. It is better to think about acceleration in units of speed change per second (that is, meters per second *per second*).

Sports car

Speed goes from 0 to 100 km/h in 5 seconds

$$\text{Acceleration} = \frac{\text{Change in speed}}{\text{Time}} = \frac{60 \text{ mph}}{5 \text{ seconds}} = \frac{100 \text{ km/h} - 0 \text{ km/h}}{5 \text{ s}} = 20 \text{ km/h per second} = \mathbf{20\ km/h/s}$$

Figure 4.11: *The acceleration of a sports car.*

Plug in values:

$$\frac{50 \text{ m/s}}{\text{s}}$$

Clear the compound fraction:

$$\frac{50 \text{ m}}{\text{s}} \times \frac{1}{\text{s}} = \frac{50 \text{ m}}{\text{s} \times \text{s}}$$

Find units:

$$50 \frac{\text{m}}{\text{s}^2}$$

Figure 4.12: *How do we get m/s²?*

Solving Problems: Acceleration

A sailboat moves at 1 m/s. A strong wind increases its speed to 4 m/s in 3 seconds (Figure 4.13). Calculate the acceleration.

1. Looking for: You are asked for the acceleration in m/s^2.

2. Given: You are given the initial speed in m/s (v_1), final speed in m/s (v_2), and the time in seconds.

3. Relationships: Use the formula for acceleration: $a = \frac{v_2 - v_1}{t}$

4. Solution:

$$a = \frac{4\ \text{m/s} - 1\ \text{m/s}}{3\ \text{s}} = \frac{3\ \text{m/s}}{3\ \text{s}} = 1\ \text{m/s}^2$$

Your turn...

a. Calculate the acceleration of an airplane that starts at rest and reaches a speed of 45 m/s in 9 seconds.

b. Calculate the acceleration of a car that slows from 50 m/s to 30 m/s in 10 seconds.

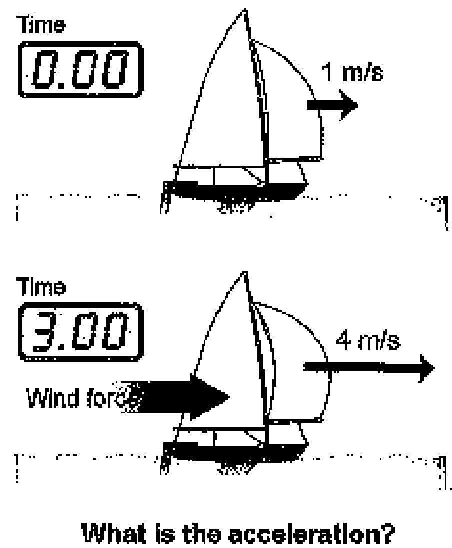


Figure 4.13: *An acceleration example.*

SOLVE FIRST LOOK LATER

a. $5\ m/s^2$

b. $-2\ m/s^2$

Acceleration on motion graphs

Acceleration on a speed vs. time graph

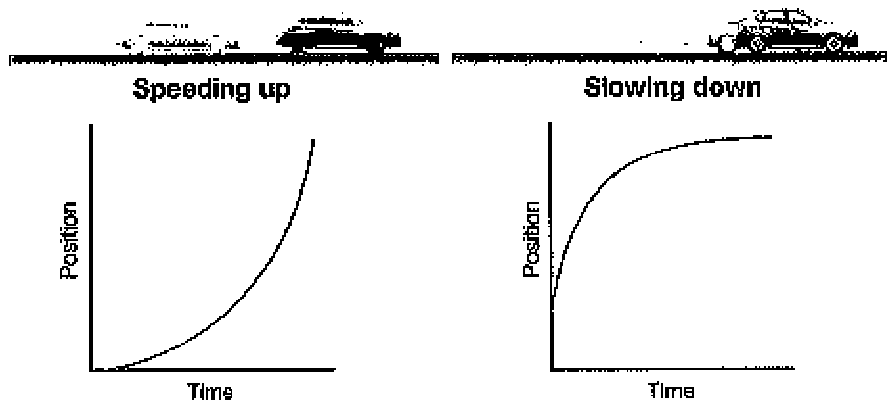
A speed vs. time graph is useful for showing how the speed of a moving object changes over time. Think about a car moving on a straight road. If the line on the graph is horizontal, then the car is moving at a constant speed (top of Figure 4.14). The upward slope in the middle graph shows increasing speed. The downward slope of the bottom graph tells you the speed is decreasing. The word *acceleration* is used for any change in velocity, either an increase or a decrease.

Positive and negative acceleration

Acceleration can be positive or negative. Positive acceleration in one direction adds more speed each second. Things get faster. Negative acceleration in one direction subtracts some speed each second. Things get slower. People sometimes use the word *deceleration* to describe slowing down.

Acceleration on a position vs. time graph

The position vs. time graph is a *curve* when there is acceleration. Think about a car with a speed that increases each second. Because it is speeding up, it covers more distance each second. The position vs. time graph gets steeper each second. The opposite happens when a car is slowing down. The speed decreases so the car covers less distance each second. The position vs. time graph gets shallower with time, becoming horizontal when the car is stopped.



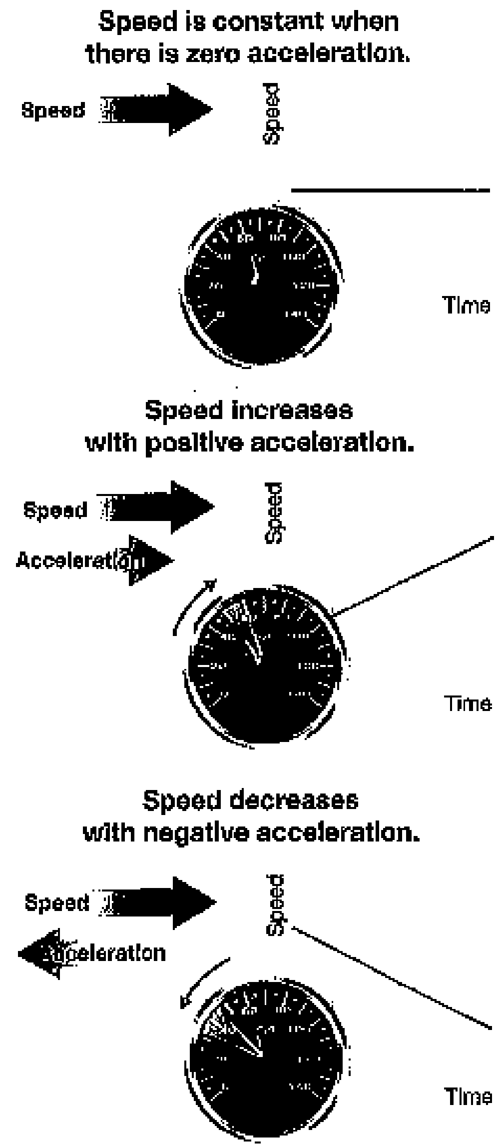
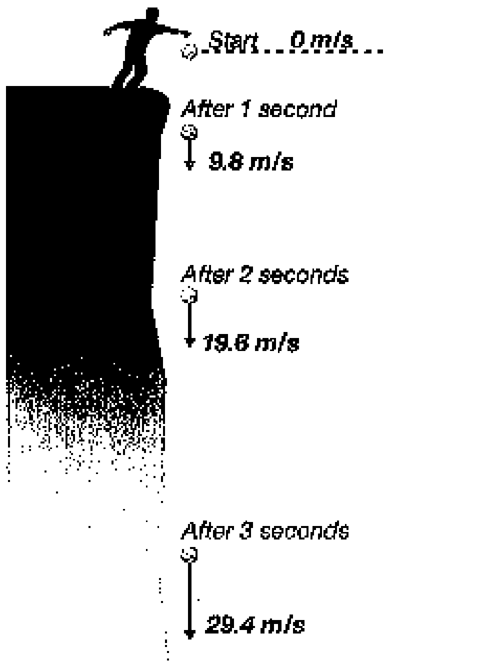


Figure 4.14: *Three examples of motion showing constant speed (top) and acceleration (middle, bottom).*

Free fall

The definition of free fall An object is in **free fall** if it is accelerating due to the force of gravity and no other forces are acting on it. A dropped ball is almost in free fall from the instant it leaves your hand until it reaches the ground. The "almost" is because there is a little bit of air friction that *does* make an additional force on the ball. A ball thrown upward is also in free fall after it leaves your hand. Even going up, the ball is in free fall because gravity is the only significant force acting on it.

The acceleration due to gravity



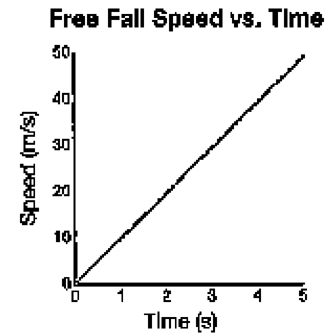
If air friction is ignored, objects in free fall on Earth accelerate downward, increasing their speed by 9.8 m/s every second. The value 9.8 m/s^2 is called the **acceleration due to gravity**. The lowercase letter *g* is used to represent its value. When you see the lowercase letter *g* in a physics question, you can substitute the value 9.8 m/s^2.

Constant acceleration The speed vs. time graph in Figure 4.15 is for a ball in free fall. Because the graph is a straight line, we know the speed increases by the same amount each second. This means the ball has a *constant acceleration*. Don't confuse constant speed with constant acceleration! Constant acceleration means an object's *speed* changes by the same amount each second.

VOCABULARY

free fall - accelerated motion that happens when an object falls with only the force of gravity acting on it.

acceleration due to gravity - the value of 9.8 m/s^2, which is the acceleration in free fall at Earth's surface, usually represented by the lowercase letter *g*.



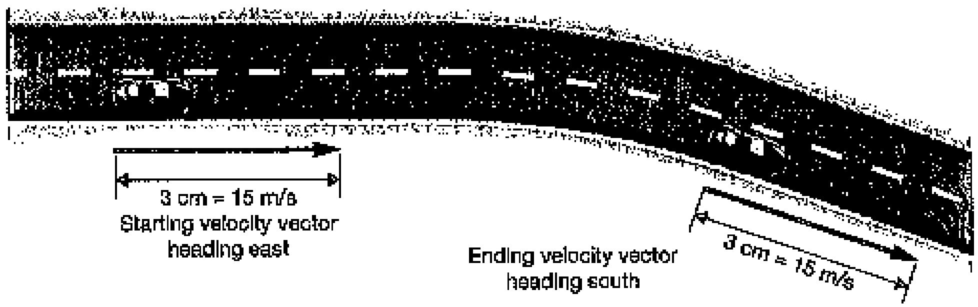
Time (s)	Speed (m/s)
0	0
1	9.8
2	19.6
3	29.4
4	39.2
5	49.0

Figure 4.15: *A dropped ball increases its speed by 9.8 m/s each second, so its constant acceleration is 9.8 m/s^2.*

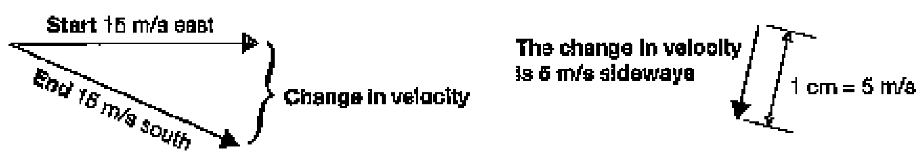
Acceleration and direction

A change in direction is acceleration If an object's acceleration is *zero*, the object can only move at a constant speed *in a straight line* (or be stopped). A car driving around a curve at a constant speed is accelerating (in the "physics sense") because its direction is changing (Figure 4.16). Acceleration occurs whenever there is a change in speed, direction, or both.

***What change in direction* means** What do we mean by *change in direction*? Consider a car traveling east. Its velocity is drawn as an arrow pointing east. Now suppose the car turns southward a little. Its velocity vector has a new direction.



Drawing vectors When drawing velocity vectors, the length represents the speed. A 2 cm vector stands for 10 m/s (22 mph). A 4 cm vector is 20 m/s, and so on. At this *scale*, each centimeter stands for 5 m/s. You can now find the change in velocity by measuring the length of the vector that goes from the old velocity vector to the new one.



Turns are caused by sideways accelerations The small red arrow in the graphic above represents the difference in velocity before and after the turn. The change vector is 1 centimeter long, which equals 5 m/s. Notice the speed is the same before and after the turn! However, the change in direction is a *sideways* change of velocity. This change is caused by a *sideways acceleration*.

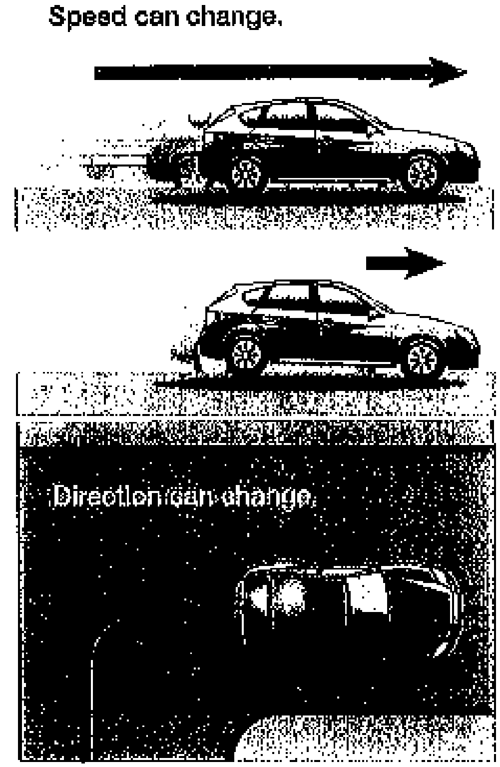


Figure 4.16: *A car can change its velocity by speeding up, slowing down, or turning. The car is accelerating in each of these cases.*

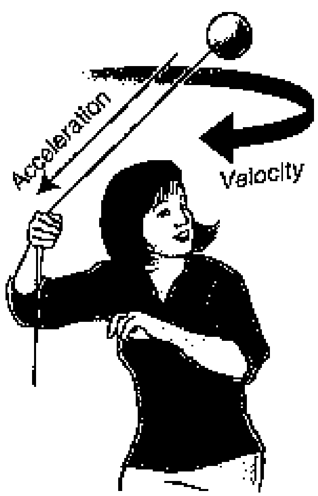
Curved motion

Acceleration and curved motion Like velocity, acceleration has direction and is a vector. Curved motion is caused by sideways accelerations. Sideways accelerations cause velocity to change direction, which results in turning. Turns create curved motion.

An example of curved motion As an example of curved motion, imagine a soccer ball kicked into the air. The ball starts with a velocity vector at an upward angle (Figure 4.17). The acceleration of gravity bends the trajectory more toward the ground during each second the ball is in the air. Therefore, gravity accelerates the ball downward as it moves through the air. Near the end of the motion, the ball's velocity vector is angled down toward the ground. The path of the ball makes a bowl-shaped curve called a *parabola*.

Projectiles A soccer ball is an example of a **projectile**. A projectile is an object moving under the influence of only gravity. The action of gravity is to constantly turn the direction of the velocity vector more and more downward. Flying objects such as airplanes and birds are *not* projectiles, because they are affected by forces generated from their own power.

Circular motion



Circular motion is another type of curved motion. An object in circular motion has a velocity vector that constantly changes direction. Imagine whirling a ball around your head on a string. You have to pull the string to keep the ball moving in a circle. Your pull accelerates the ball toward you. That acceleration is what bends the ball's velocity into a circle with you at the center. Circular motion always has an acceleration that points toward the center of the circle. In fact, the direction of the acceleration changes constantly so it *always* stays pointed toward the center of the circle.

VOCABULARY

projectile - an object moving through space and affected only by gravity.

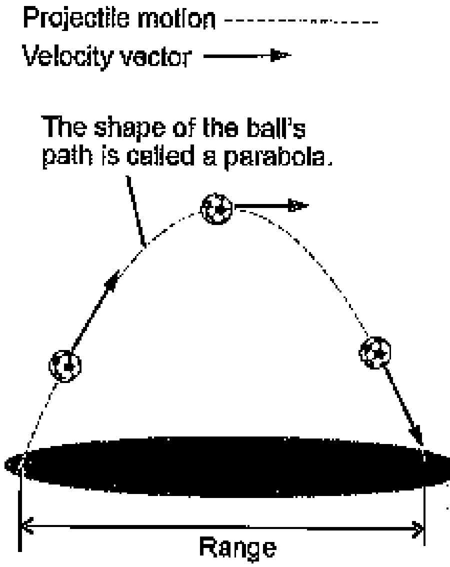
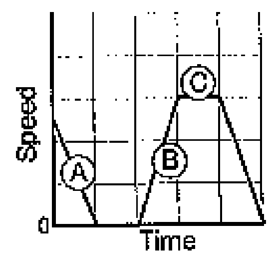


Figure 4.17: *A soccer ball in the air is a projectile. The path of the ball is a bowl-shaped curve called a parabola.*

Section 4.3 Review

1. Nearly all physics problems will use the unit m/s^2 for acceleration. Explain why the seconds are squared. Why isn't the unit given as m/s, as it is for speed?
2. Suppose you are moving forward with a velocity of 10 m/s. What happens to your speed if you have a *negative* acceleration? Do you speed up or slow down?
3. A rabbit starts from a resting position and is moving at 6 m/s after 3 seconds. What is the acceleration of the rabbit? (Figure 4.18)
4. You are running a race and you speed up from 3 m/s to 5 m/s in 4 seconds.
   a. What is your change in speed?
   b. What is your acceleration?
5. Does a car accelerate when it goes around a corner at a constant speed? Explain your answer.
6. A sailboat increases its speed from 1 m/s to 4 m/s in 3 seconds. What will the speed of the sailboat be at 6 seconds if the acceleration stays the same? (Figure 4.19)
7. The graph at the right shows the speed of a person riding a bicycle through a city. Which point (A, B, or C) on the graph is a place where the bicycle has speed but no acceleration? How do you know?



8. What happens to the speed of an object that is dropped in free fall?
9. A ball is in free fall after being dropped. What will the speed of the ball be after 2 seconds of free fall?
10. What happens when velocity and acceleration are at right angles to each other? What kind of motion occurs?
11. The Earth moves in a nearly perfect circle around the Sun. Assume the speed stays constant. Is the Earth accelerating?

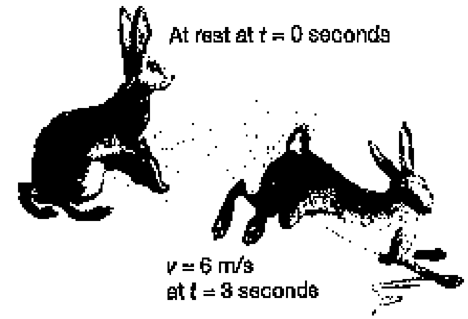


Figure 4.18: *Question 3.*

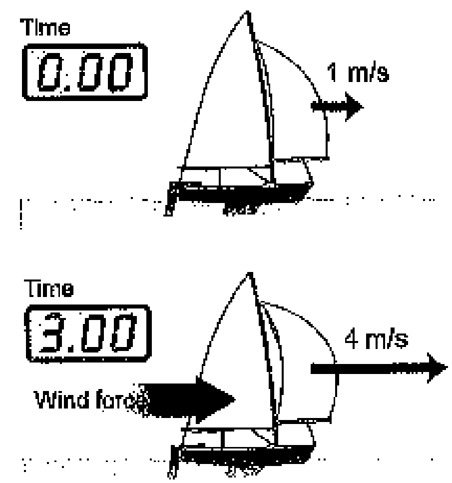


Figure 4.19: *Question 6.*

ks 1 m/s fo
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Hint: Use the
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(m)

nd warm-up?

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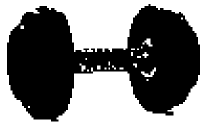
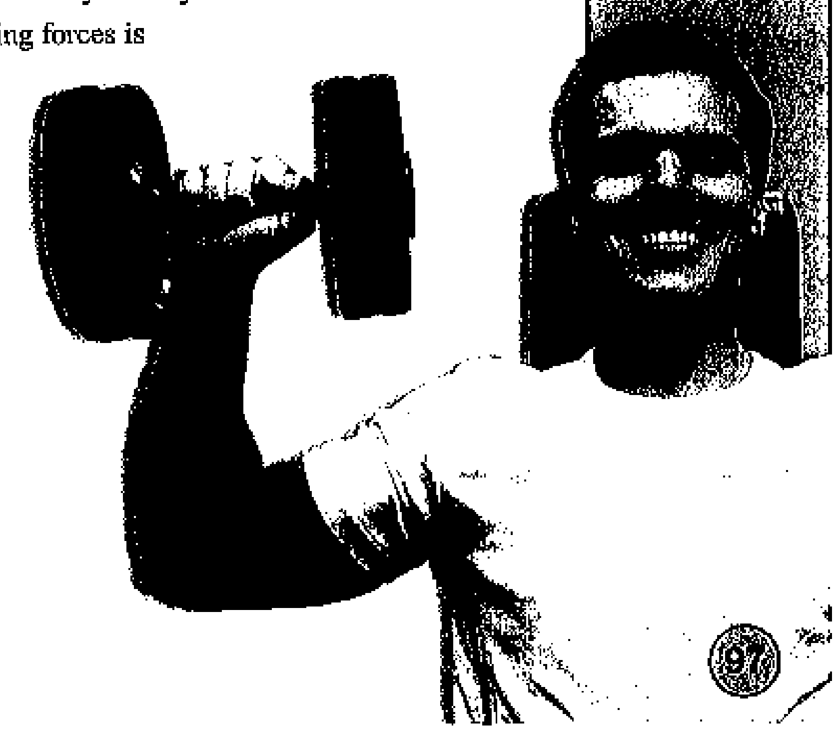
Chapter 5

Force



Every year, all over the world, competitions are held that require strength and a knowledge of force. Athletes compete in events with names like the Giant Log Lift, the Pillars of Hercules, the Atlas Stones, and the Plane Pull. As you might imagine, moving a giant log or a plane requires a tremendous amount of force. How can athletes achieve these amazing feats? There is a good chance that during their training, they thought about how best to apply force so that they could lift a giant log, pull a plane, or lift a 160-kilogram Atlas Stone.

Forces are created and applied every time something moves. Forces, such as weight, are even present when objects are not moving. Your body uses forces even when your heart is beating and when you are walking upstairs. And force is necessary when you want to pick up or move something that is very heavy. Understanding forces is fundamental to understanding how tasks are best accomplished in nature and by people. Read this chapter to learn more about how forces are created, measured, described, and used in daily life.



Key Questions

- ✔ ***How are you affected by forces right now?***
- ✔ ***What is friction and how is it useful?***
- ✔ ***What happens when an object experiences net force?***

5.1 Forces

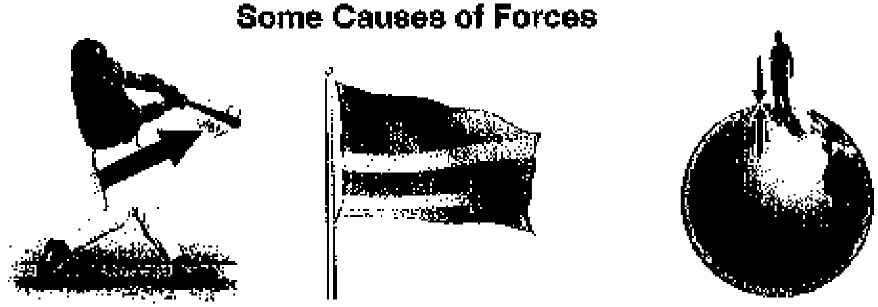
Force is a very important concept in physics and in everyday life. In this chapter, you will learn where forces come from, how they are measured, and how they are added and subtracted.

The cause of forces

What are forces? A **force** is a push or a pull. Technically, force is the *action* that has the ability to change motion. You need force to start an object moving. You also need force to change an object's motion if it is already moving. Forces can increase or decrease the speed of a moving object. Forces can also change the direction in which an object is moving.

How are forces created? Forces are created in many ways. For example, your muscles create force when you swing a baseball bat. On a windy day, the movement of air can create forces. Earth's gravity creates a force called *weight* that pulls on everything around you. Each of these actions creates forces and through those forces, each can change an object's motion.

Some Causes of Forces



Muscles — Moving matter (like wind) — Massive objects (like planets)

The four elementary forces All of the forces we know of in the universe come from four elementary forces. Figure 5.1 describes the four elementary forces. If you study physics or chemistry, you will learn more about the strong and weak forces. These forces are only important inside the atom and in certain types of radioactivity. However, the electromagnetic force and gravity are important in almost all areas of human life, including technology.

VOCABULARY

force - a push or a pull, or any action that involves the interaction of objects and has the ability to change motion.

The Four Elementary Forces

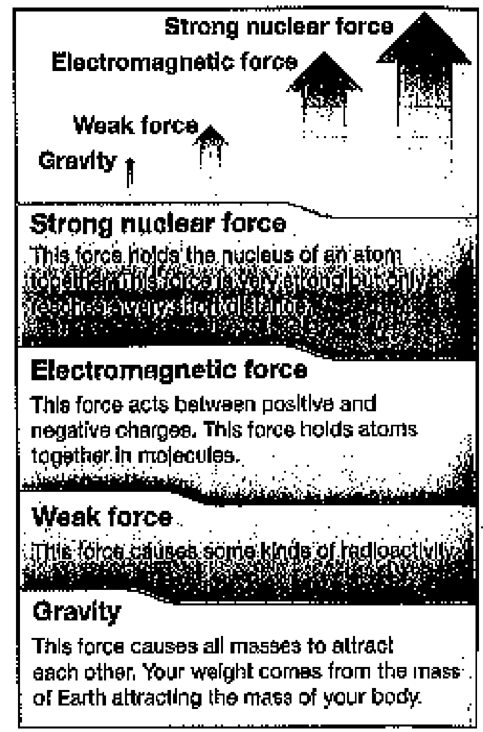


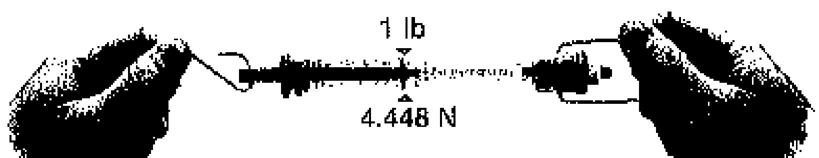
Figure 5.1: *All forces in the universe come from only four elementary forces.*

Units of force

Pounds Imagine mailing a package at the post office. How does the postal clerk know how much you should pay? You are charged a certain amount for every pound of *weight*. The **pound** (lb) is a unit of force commonly used in the United States. When you measure weight in pounds on a scale, you are measuring the force of gravity acting on an object (Figure 5.2). For smaller amounts, pounds are divided into ounces (oz). There are 16 ounces in 1 pound.

The origin of the pound The pound is based on the Roman unit *libra*, which means "balance." This is why the abbreviation for pound is lb. The word *pound* comes from the Latin *pondus*, meaning "weight." The definition of a pound has varied over time and from country to country.

Newtons Although we use pounds all the time in our everyday life, scientists prefer to measure forces in *newtons*. The **newton** (N) is an SI of force. The newton is defined by how much a force can change the motion of an object. A force of 1 newton is the exact amount of force needed to cause a mass of 1 kilogram to speed up (or slow down) by 1 m/s each second (Figure 5.2). We call the SI unit of force the *newton* because force is defined by Newton's laws. The newton is a useful way to measure force because it connects force directly to its effect on motion.



1 pound = 4.448 newtons

Unit conversions The newton is a smaller unit of force than the pound. One pound of force equals 4.448 newtons. That makes the newton a little less than a quarter of a pound. This is about the weight of a stick of butter. As another example, a 100-pound person weighs 444.8 newtons. In SI units, the mass of a 100-pound person (on Earth) is about 45 kilograms. If you do the math (444.8 ÷ 45) you will find that 1 kg of mass has a weight of 9.8 newtons of force.

VOCABULARY

pound - the English unit of force equal to 4.448 newtons.

newton - the SI unit of force, equal to the force needed to make a 1-kg object accelerate at 1 m/s^2.

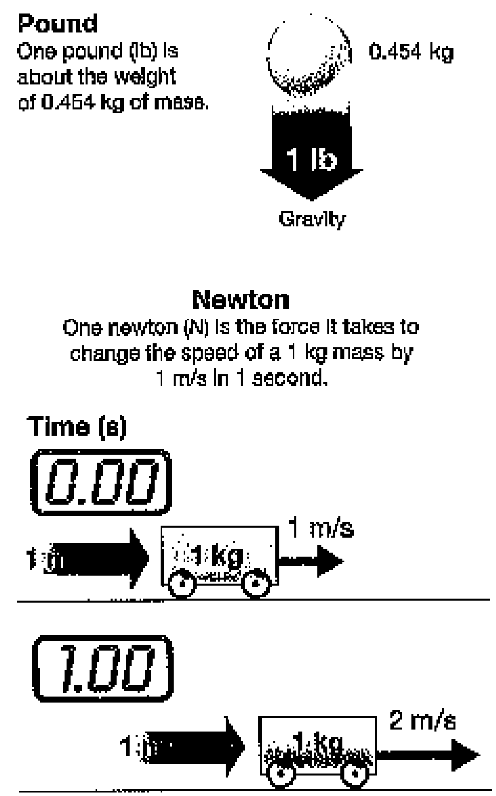


Figure 5.2: *The definitions of* newton *and* pound.

The force vector

Force is a vector The direction of a force makes a big difference in what the force can do. That means force is a *vector*, like velocity or position. To predict the effect of a force, you need to know both its *strength* and its *direction*. Strength is usually measured in newtons. Direction may be given in words, such as 5 newtons *down*, or in symbols. Arrows are often used to show the direction of forces in diagrams (Figure 5.3).

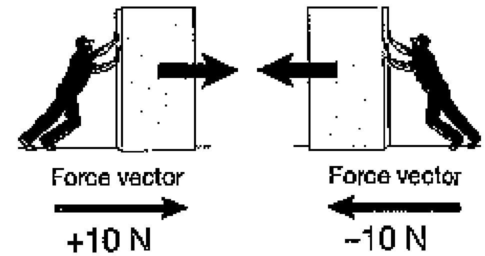


Figure 5.3: *Positive and negative numbers are used to indicate the direction of force vectors.*

Using positive and negative numbers Forces may be assigned positive and negative values to tell their directions. For example, suppose a person pushes with a force of 10 newtons to the right (Figure 5.3). The force vector is +10 N. A person pushing with the same force to the left would create a force vector of −10 N. The negative sign indicates that the −10 N force is in the opposite direction from the +10 N force. We usually choose positive values to represent forces directed up, to the right, to the north, or to the east.

Drawing a force vector It is sometimes helpful to show both the strength and direction of a force vector as an arrow on a graph. The length of the arrow represents the strength of the force. The arrow points in the direction of the force. The *x*- and *y*-axes show the strength of the force in the *x* and *y* directions.

Scale When drawing a force vector to show its strength, you must choose a scale. For example, suppose you want to draw a force of 5 N pointing straight up (*y*-direction). You might use a scale of 1 cm = 1 N. At this scale, the force vector is a 5-cm long arrow pointing up, along the *y*-axis on your graph (Figure 5.4). A 5 N horizontal force would be drawn along the *x*-axis with a 5-cm long arrow pointing to the right.

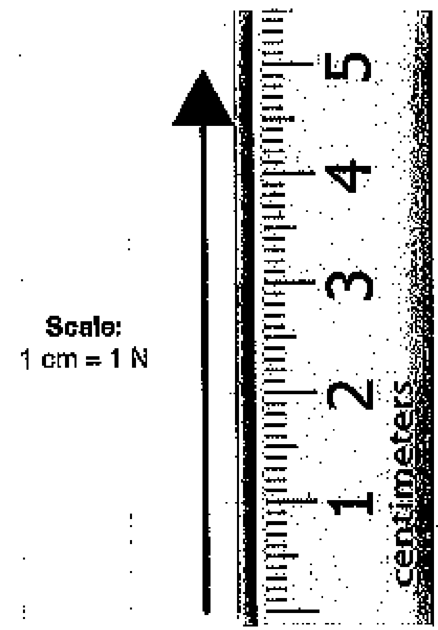


Figure 5.4: *You must use a scale when drawing a vector.*

How forces act

Contact forces There are two ways that objects can affect each other through forces. One way is the result of direct contact. The force between two people pulling on a rope is a good example of a force that occurs through direct contact (Figure 5.5). A contact force is transmitted by matter directly touching other matter. The wind acting to slow a parachute is also a contact force because air is matter. The force comes from air contacting the parachute. In the next section, you will learn about *friction*, another contact force.

Forces that act through space Now think about Earth and the Moon. If Earth were to disappear, the Moon would sail off into space by itself. The Moon doesn't fly off because a force exists between Earth and the Moon. That force is called *gravity*. Gravity provides the force that keeps Earth and the Moon together in orbit. But, exactly how does "gravity" get from Earth to the Moon? Space is empty of matter, so the force cannot be a contact force.

Some examples The force of gravity between Earth and the Moon appears to be what people once called "action-at-a-distance." The force between two magnets is another force that acts at a distance. So is the force that causes electricity. Table 5.1 summarizes the two types of forces.

Table 5.1: Types of Forces

Contact Forces	"At-a-distance" Forces
friction	gravity
normal force	electricity
tension, air resistance, spring	magnetism

The force field Today, we know that a true "action-at-a-distance" force is impossible. The force of gravity actually acts in two steps. First, the mass of Earth creates a *gravitational field* that fills the space around Earth with potential energy. Second, the gravitational field of Earth creates a force on the Moon. The gravitational force is carried from Earth to the Moon by a *force field*. In fact, if Earth were to vanish instantly, the Moon would continue to be affected by Earth's gravity for a few seconds. This is because the force field "flows" between Earth and the Moon quickly, *but not instantly*.

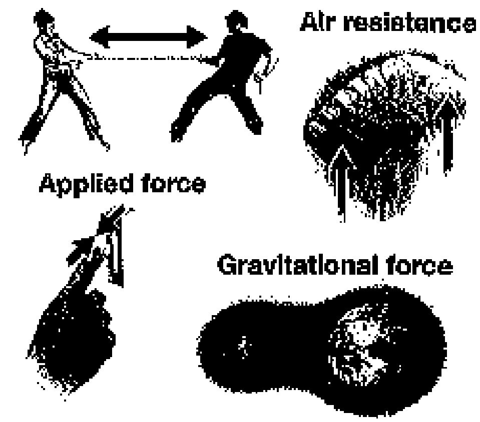


Figure 5.5: *Contact forces and a force that acts through a force field.*

STUDY SKILLS

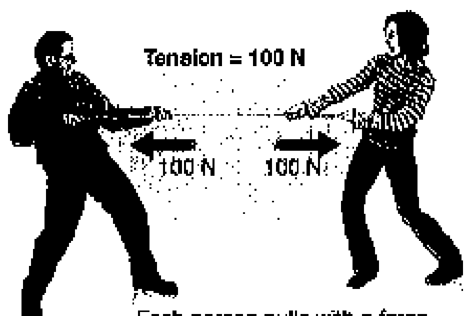
Defining Forces

Pick a term that is listed in Table 5.1 but that is not described on this page (friction, normal force, or spring force). Find out what the term means. You can do research and find the answer on your own or ask someone who is knowledgeable on the subject.

Contact forces from ropes and springs

Two ways contact forces occur Ropes and springs are often used to make and apply forces. Ropes are used to transfer forces or change their direction. Springs are used to make and control forces.

Tension



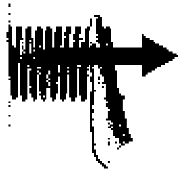
Each person pulls with a force of 100 newtons, so the tension is 100 newtons.

The pulling force carried by a rope is called **tension**. *Tension always acts along the direction of the rope.* A rope carrying a tension force is stretched tight. The two people in the diagram at the left are each pulling on the rope with a force of 100 newtons. Tension is defined as the force with which a rope is pulled in *each* direction, so the tension in the rope is 100 newtons. Ropes do *not* carry pushing forces. This is obvious if you have ever tried pushing a rope!

Spring forces

Stretch a spring and the spring exerts an opposite force back on your hand.

Compress a spring and the spring also exerts an opposite force back on your hand.



Springs are used to make or control forces. A spring creates a force when you stretch it or squeeze it away from its resting shape. The force from a spring always acts to return the spring to its resting shape. If you stretch a spring (**extension**), the spring acts to make itself shorter, pulling back on your hand. If you squeeze a spring (**compression**), the spring tries to get longer again and pushes back on your hand.

Spring forces vary in strength The force created by a spring is proportional to the ratio of the extended or compressed length divided by the original (resting) length. If you stretch a spring twice as much, it makes a force that is twice as strong.

VOCABULARY

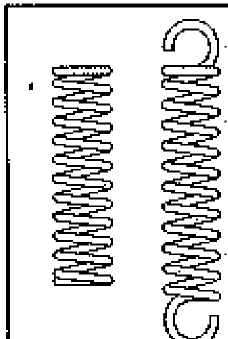
tension - a pulling force that acts in a rope, string, or other object.

extension - a "stretch," or increase in size.

compression - a "squeeze," or decrease in size.

TECHNOLOGY

Springs



2 common types of springs

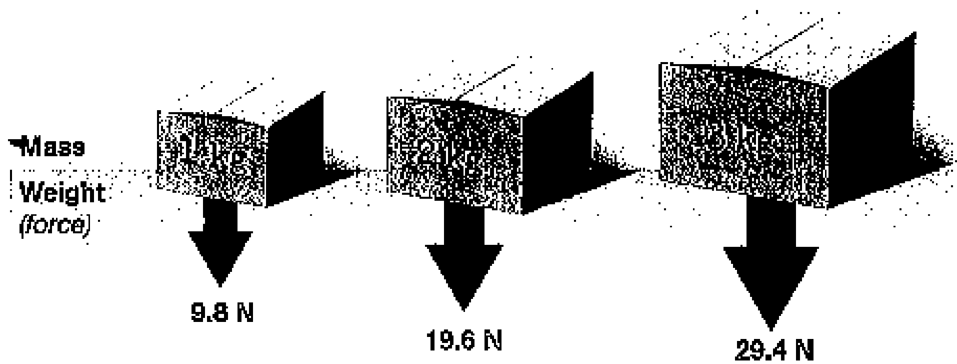
Two of the many types of springs are extension springs and compression springs. Extension springs are designed to be stretched. They often have loops on either end. Compression springs are designed to be squeezed. They are usually flat on both ends. Can you find both types in springs in your classroom?

1. What is the spring used for?
2. What would happen if the spring broke?

Gravity

Gravitational force depends on mass

The force of gravity on an object is called *weight*. At Earth's surface, gravity exerts a force of 9.8 N on every kilogram of mass. Therefore, on Earth, the weight of any object is its mass multiplied by 9.8 N/kg. For example, a 1-kilogram mass has a weight of 9.8 N, a 2-kilogram mass has a weight of 19.6 N, and so on. Because weight is a force, it is measured in units of force such as newtons and pounds.



Weight vs. mass

Weight and mass are not the same. Mass is a fundamental property of matter measured in kilograms (kg). Weight is a *force* measured in *newtons* (N). Weight depends on mass *and* gravity. For example, how much you weigh depends on your mass and the strength of gravity at your location. It is easy to confuse mass and weight because they seem similar. Heavy objects (more weight) have lots of mass and light objects (less weight) have little mass. But, it's important to remember the difference when doing physics.

Weight is a force that depends on mass and gravity.

Weight is less on the Moon

A 10-kilogram rock has the same mass no matter where it is in the universe. The rock's *weight*, however, depends on where it is located. On Earth, the rock weighs 98 newtons. But on the Moon, it weighs only 16 newtons (Figure 5.6). On the Moon, the rock's weight would be one-sixth the rock's weight on Earth because the strength of gravity on the Moon is one-sixth the strength of gravity on Earth.

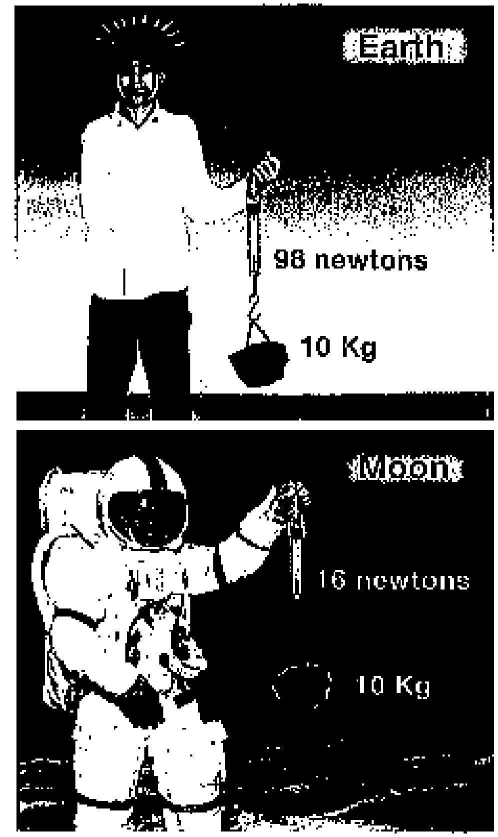


Figure 5.6: *A 10-kilogram rock weighs 98 newtons on Earth but only 16 newtons on the Moon.*

Calculating weight

The weight formula The weight formula lets you calculate the weight of an object if you know the object's mass and the strength of gravity at the object's location. Three forms of the weight formula are given in Table 5.2. Use the appropriate form to find weight, mass, or the strength of gravity if you know any two of the three values.

WEIGHT

Strength of gravity (N/kg)

Weight (N) $$W = mg$$

Mass (kg)

g is the symbol for gravity The strength of gravity at Earth's surface is so important to our everyday life that we give it a special symbol, the lowercase letter g. When you see a g in a formula you can usually substitute the value $g = 9.8$ N/kg. Of course, that assumes the formula is being applied at the surface of Earth! Elsewhere in the universe g has different values. You sometimes see g written with units of m/s^2, for example, $g = 9.8$ m/s^2. This is really the same g expressed as the acceleration of a 1-kg mass under the influence of gravity.

Table 5.2: Different Forms of the Weight Formula

Use . . .	if you want to find: . .	and you know. . .
$W = mg$	weight (W)	mass (m) and strength of gravity (g)
$m = W/g$	mass (m)	weight (W) and strength of gravity (g)
$g = W/m$	strength of gravity (g)	weight (W) and mass (m)

STUDY SKILLS

Different Ways to Show "Divided By"

Below are three different ways to show the equation "mass equals weight divided by gravity." Notice the different ways to show "divided by." You should familiarize yourself with all three versions.

Mass = weight divided by gravity

$m = W/g$

$m = \frac{W}{g}$

$m = W \div g$

Some Notes about Drawing Force Vectors

1. Force vectors should always be drawn in the direction of the force they represent.
2. Force vectors should be drawn to scale if possible, with length proportional to strength.
3. A force on a surface can be shown as pointing toward the surface or away from it. What matters is that the direction is clear so you know what the net force is in a certain direction.

Solving Problems: Weight and Mass

Calculate the weight of a 60-kilogram person (in newtons) on Earth and on Mars ($g = 3.7$ N/kg on Mars) (Figure 5.7).

1) Looking for: You are asked for a person's weight on Earth and on Mars.

2) Given: You are given the person's mass and the value of g on Mars.

3) Relationships: $W = mg$

4) Solution: For the person on Earth:
$W = mg$
$W = (60\text{ kg})(9.8\text{ N/kg}) = 588$ newtons

For the person on Mars:
$W = mg$
$W = (60\text{ kg})(3.7\text{ N/kg}) = 222$ newtons

Notice that while the masses are the same, the weight is much less on Mars.

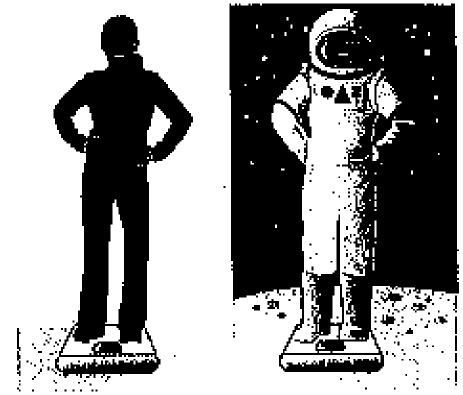


Figure 5.7: *How does the weight of a person on Earth compare to the weight of the same person on Mars?*

Your turn...

a. Calculate the mass of a car that weighs 19,600 N on Earth.

b. A 70-kg person travels to a planet where he weighs 1,750 N. What is the value of g on that planet?

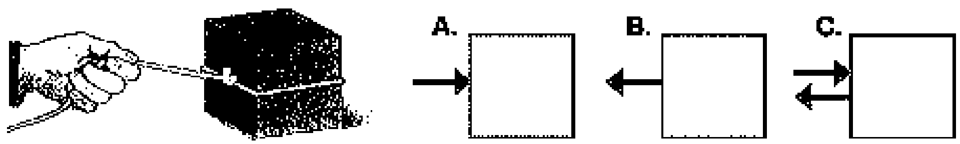
SOLVE FIRST LOOK LATER

a. 2,000 kg

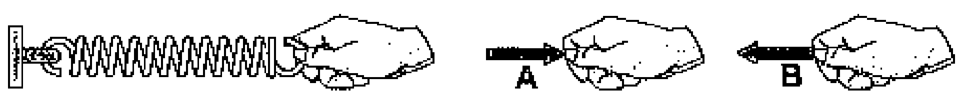
b. 25 N/kg

Section 5.1 Review

1. Name three situations in which force is created. Describe the cause of the force in each situation.
2. Which of the following are units of force?
   a. kilograms and pounds
   b. newtons and pounds
   c. kilograms and newtons
3. Which is greater: a force of 10 N or a force of 5 lbs?
4. A rope is used to apply a force to a box. Which drawing shows the force vector drawn correctly?



5. What is the difference between contact forces and forces that act through a force field?
6. A spring is stretched as shown. Which drawing shows the force exerted *by the spring*? (*Hint*: *Not* the force *on* the spring.)



7. If the strength of gravity is 9.8 newtons per kilogram, that means:
   a. each newton of force equals 9.8 pounds.
   b. each pound of force equals 9.8 newtons.
   c. each newton of mass weighs 9.8 kilograms.
   d. each kilogram of mass weighs 9.8 newtons.
8. An astronaut in a spacesuit has a mass of 100 kilograms. What is the weight of this astronaut on the surface of the Moon where the strength of gravity is approximately one-sixth that of Earth?
9. What is the weight (in newtons) of a bowling ball that has a mass of 3 kilograms?

SOLVE IT!

Calculating Mass from Weight

Use the steps on page 105 to solve the following problems.

1. What is the mass of an object with a weight of 35 newtons? Assume the object is on Earth's surface.
2. Which is greater: A force of 100 N or the weight of 50 kilograms on Earth's surface?
3. The mass of a bag of potatoes is 0.5 kg. Calculate the weight of the potatoes in newtons.

SCIENCE FACT

Contact forces are actually acting through force fields too! When you push a box, the atoms in your hand are electrically repelling the atoms in the box. The force is carried between the atoms of your hand and the atoms of the box by trillions of tiny electrical force fields. In reality, *all* forces act through force fields once you get to the atomic level! We don't notice because atoms are so small.

5.2 Friction

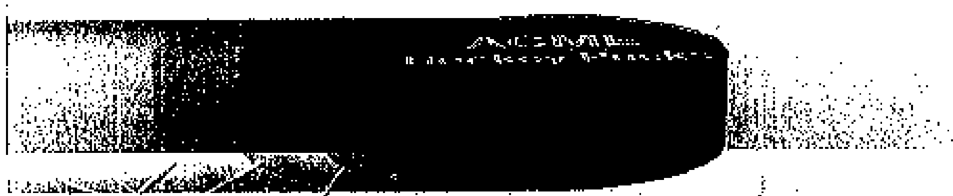
Friction is a force that resists motion. Friction is found everywhere in our world. You feel the effects of friction when you swim, ride in a car, walk, and even when you sit in a chair. Friction can act when an object is moving or when it is at rest. Many types of friction exist. Figure 5.8 shows some common examples.

Some causes of friction

The cause of friction Imagine looking through a microscope at two smooth surfaces touching each other. You would see tiny hills and valleys on both sides. As surfaces slide (or try to slide) across each other, the hills and valleys grind against each other. This is a cause of friction. The tiny hills may change shape or wear away. If you rub sandpaper on a piece of wood, friction affects the wood's surface and makes it either smoother (hills wear away) or rougher (hills change shape).

Microscopic hills and valleys cause friction between smooth surfaces.

Two surfaces are involved Friction depends on *both* of the surfaces that are in contact. The force of friction on a rubber hockey puck is very small when it is sliding on ice. But the same hockey puck sliding on a piece of sandpaper experiences a large friction force. When the hockey puck slides on ice, a thin layer of water between the rubber and the ice allows the puck to slide easily. Water and other liquids, such as oil, can greatly reduce the friction between surfaces.



VOCABULARY

friction - a force that resists motion.

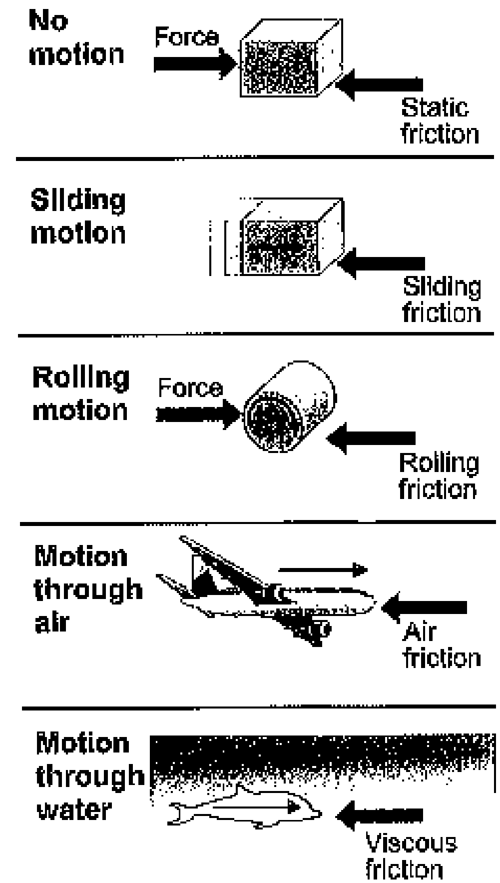


Figure 5.8: *There are many types of friction.*

Identifying friction forces

Direction of the friction force

We think of friction as a force, measured in newtons just like any other force. You draw the force of friction with a force vector. To figure out the direction of the vector, always remember that *friction resists motion between surfaces*. The force of friction acting *on* a surface always points opposite the direction of the motion *of that surface*. Imagine pushing a heavy box across the floor (Figure 5.9). If the box is moving to the right, then friction acts to the left, against the surface of the box touching the floor. If the box were moving to the left instead, the force of friction would act toward the right. This is what we mean when we say friction resists motion.

Sliding friction

Sliding friction is a force that resists dry sliding motion between any two surfaces. If you push a box across the floor toward the right, sliding friction acts toward the left, slowing down the motion of the box. The friction force acts between the floor and the bottom surface of the box. Let's say you stop pushing the box, but it keeps moving. Sliding friction continues to work and eventually slows the box to a stop.

Static friction

Static friction keeps an object that is standing still (at rest) from starting to move. Imagine trying to push a heavy box with a small force. The box stays at rest because the static friction force acts against your force and cancels it out. As you increase the strength of your push, the static friction also increases. Eventually, your force becomes strong enough to overcome static friction and the box starts to move (Figure 5.9). The force of static friction balances your force up to a limit. The limit of the static friction force depends on the types of surfaces, the weight of the object you are pushing, and the angle of incline of the surface.

Comparing sliding and static friction

How does sliding friction compare with static friction? If you have ever tried to move a heavy sofa or refrigerator, you probably know the answer. *It is harder to get something moving than it is to keep it moving.* This is because static friction is almost always greater than sliding friction at slow speeds.

VOCABULARY

sliding friction - the friction force that resists the motion of an object moving across a surface.

static friction - the friction force that resists the motion between two surfaces that are not moving.

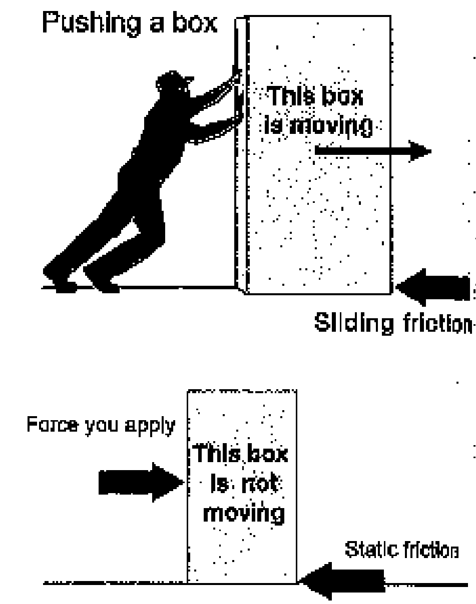


Figure 5.9: *The direction of the force of friction is opposite the direction the box is pushed.*

A model for friction

Different amounts of friction The amount of friction generated when a box is pushed across a smooth floor is very different from when it is pushed across a carpet. This is because friction depends on materials, roughness, how clean the surfaces are, and other factors. Even the friction between two identical surfaces changes as the surfaces are polished by sliding motion. No single formula can accurately describe all types of friction.

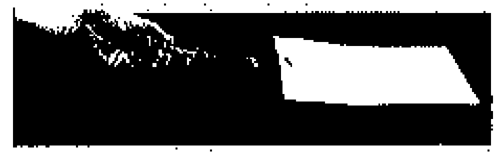
An example An easy experiment to measure friction is to pull a piece of paper across a table with a force scale. The paper slides smoothly, and the scale measures almost no force. Now put a brick on the piece of paper (Figure 5.10). Friction increases and you must pull with a greater force to move the paper.

Friction depends on the force between surfaces Why does the brick have an effect on friction? The two surfaces in contact are still the paper and the tabletop, but the brick causes the paper to press harder into the table's surface. The tiny hills and valleys in the paper and in the tabletop are pressed together with a much greater force, so the friction increases. The same is true of most dry sliding friction. Increasing the force that pushes surfaces together increases the amount of friction.

The greater the force squeezing two surfaces together, the greater the friction force.

Why sliding friction increases with weight The friction force between two smooth, hard surfaces is approximately proportional to the force squeezing the surfaces against each other. Consider sliding a heavy box across a floor. The force between the bottom of the box and the floor is the weight of the box. Therefore, the force of friction is proportional to the weight of the box. If the weight doubles, the force of friction also doubles. This rule is NOT true if one or both surfaces are wet, or if they are soft.

It takes very little force to slide paper across a table.



Adding a brick on top of the paper greatly increases the friction force.

Figure 5.10: *Friction increases greatly when a brick is placed on the paper.*

Reducing the force of friction

All surfaces experience some friction

Unless a force is constantly applied, friction will slow all motion to a stop eventually. For example, bicycles have low friction, but even the best bicycle slows down as you coast on a level road. It is impossible to completely eliminate friction. However, many clever inventions have been devised to reduce friction. You use them every day.

Lubricants reduce friction in machines

Putting a liquid, such as oil, between two sliding surfaces keeps them from touching each other. The tiny hills and valleys don't become locked together, so there is less friction. The liquid also keeps the surfaces from wearing away as quickly. You add oil to a car's engine so that the moving parts slide or turn with less friction. Even water can be used to reduce friction between objects if they are not too hot.

Ball bearings

A ball bearing you might find in a machine

Ball bearings reduce friction in rotating motion (Figure 5.11). Ball bearings change sliding motion into rolling motion, which has much less friction. For example, a metal shaft rotating in a hole rubs and generates a lot of friction. Ball bearings that go between the shaft and the inside surface of the hole allow the shaft to spin more easily. The shaft rolls on the bearings instead of rubbing against the walls of the hole. Well-oiled bearings rotate easily and greatly reduce friction.

Magnetic levitation

Another method of decreasing friction is to separate the two surfaces with a cushion of air. A hovercraft floats on a cushion of air created by a large fan. Magnetic forces can also be used to separate surfaces. A magnetically levitated (or maglev) train uses magnets that run on electricity to float on the track once the train is moving (Figure 5.12). There is no contact between train and track, so there is far less friction than with a standard train on tracks. The ride is smoother, so maglev trains can move at very fast speeds. Maglev trains are not widely used yet because they are much more expensive to build than regular trains. They may become more popular in the future.

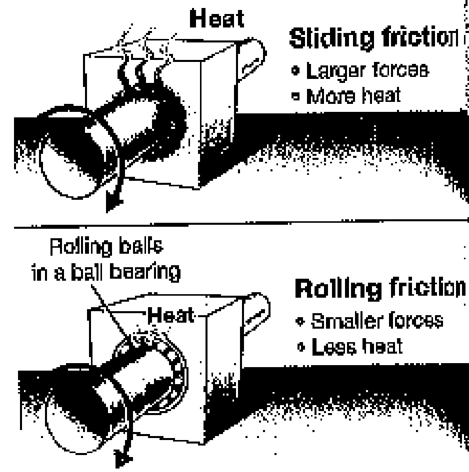


Figure 5.11: *The friction between a shaft (the long pole in the picture) and the inner surface of the hole produces a lot of heat. Friction can be reduced by placing ball bearings between the shaft and the hole surface.*

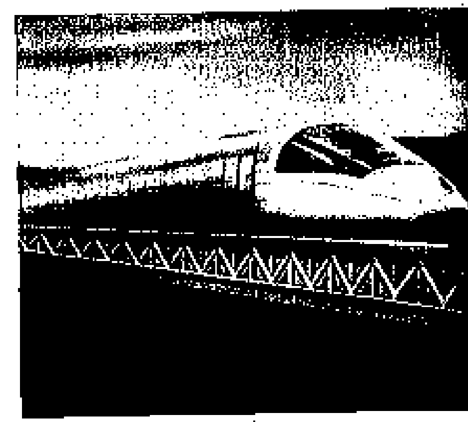
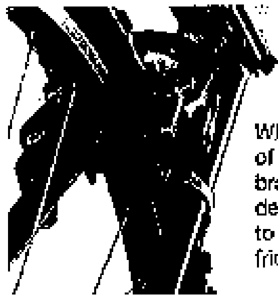


Figure 5.12: *With a maglev train, there is no contact between the moving train and the rail—and thus there is little friction.*

Using friction

Friction is useful for brakes and tires



What part of a bicycle brake is designed to increase friction?

There are many occasions when friction is very useful. For example, the brakes on a bicycle create friction between the brake pads and the rim of the wheel. Friction makes the bicycle slow down or stop. Friction is also needed to make a bicycle move. Without friction, the bicycle's tires would not grip the road.

Tires designed for bad weather

Friction is also important to anyone driving a car. Tires are specially designed to maintain friction on pavement in rain or snow. Tire treads have grooves that allow space for water to be channeled away where the tire touches the road (Figure 5.13). This allows good contact between the rubber and the road surface. Special groove patterns along with tiny slits are used on snow tires to increase traction in snow. These grooves and slits keep snow from getting packed into the treads.

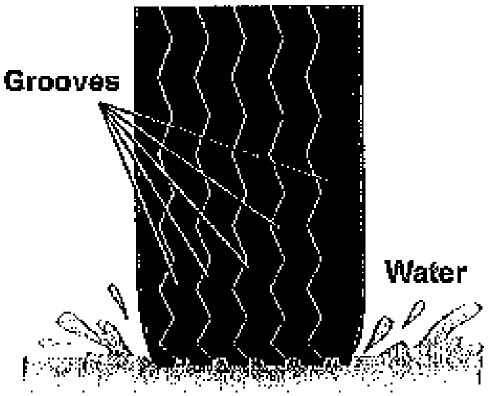
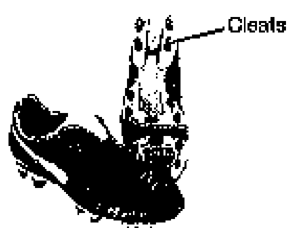


Figure 5.13: *Grooved tire treads allow space for water to be channeled away from the road–tire contact point, allowing for more friction in wet conditions.*

Nails

Friction even keeps nails in place (Figure 5.14). When a nail is hammered into wood, the wood pushes against the nail on all sides. The force of the wood against the nail surface creates a lot of friction. Each hit of the hammer pushes the nail deeper into the wood. The deeper the nail goes, the more surface there is for friction to grab onto.

Cleated shoes



Shoes are designed to increase the friction between your foot and the ground. Many athletes, including football and soccer players, wear shoes with cleats. Cleats are like teeth on the bottom of the shoe that dig into the ground. Players wearing cleats can apply much greater force against the ground to help them move and to keep them from slipping.

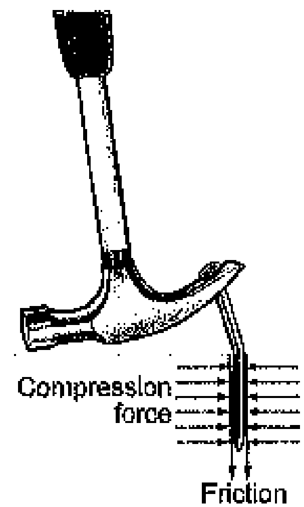
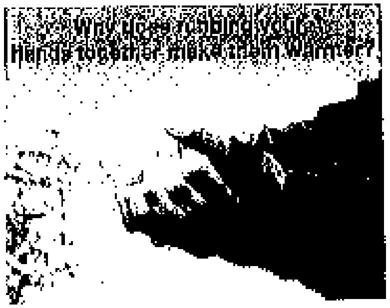


Figure 5.14: *Friction is what makes nails hard to pull out, and what gives nails the strength to hold things together.*

Friction and energy

Friction changes energy of motion into heat

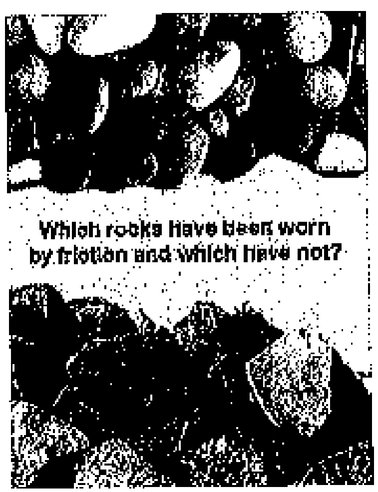

Why does rubbing your hands together make them warmer?

Earlier, we learned that energy moves through the action of forces. Energy also changes into different forms. For example, friction changes energy of motion into heat energy. You may have noticed that rubbing your hands together quickly can make them warmer. You are feeling the effect of friction changing energy of motion into heat.

Heat in machines

Friction is always present in any machine with moving parts. In small machines, the forces are low and the amount of heat produced by friction may be small. A sewing machine is an example of a small machine. Larger machines have more problems with heat. In many machines, oil is pumped around moving parts. The oil does two important things. First, oil reduces friction so less heat is generated. Second, the oil absorbs the heat and carries it away from the moving parts. Without the flow of cooling oil, moving parts in an engine would heat up too much and melt.

Friction causes wear


Which rocks have been worn by friction and which have not?

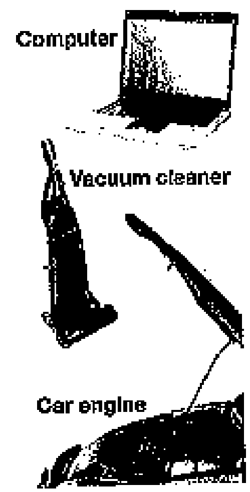
Another way friction changes energy is by wearing away moving parts. You have probably noticed that objects that slide against each other often get rounded or smoothed. Each time two moving surfaces touch each other, tiny bits of material are broken off by friction. Breaking off bits of material uses energy. Sharp corners and edges are rounded off and flat surfaces may be scratched or even polished smooth and shiny.

TECHNOLOGY

Heat and Machines

Every machine releases heat from friction. The faster the parts move, and the larger the forces inside the machine, the more heat is released. Electronic machines, such as computers, are no exception, even though they may have no moving parts! Electricity moving through wires also creates friction.

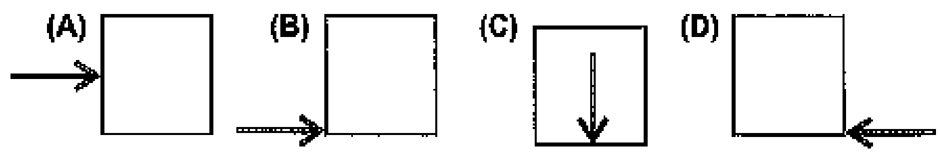
If a machine gets too hot, parts can melt and the machine may stop working. Because of this, many machines have special systems, parts, and designs to get rid of unwanted heat energy.



Here are three machines you probably see every day. How is excess heat removed from each one?

Section 5.2 Review

1. It is a common practice to put oil in a car and to change the car's oil once in a while. Why do cars need oil?
2. Which TWO of the following statements are true?
   a. Sliding friction is typically greater than static friction.
   b. Static friction is typically greater than sliding friction.
   c. Sliding friction occurs at rest and static friction occurs in motion.
   d. Static friction occurs at rest and sliding friction occurs in motion.
3. If the force squeezing two surfaces together is decreased, the force of dry sliding friction between the two surfaces will most likely:
   a. increase
   b. decrease
   c. stay about the same
4. Name three devices or inventions that are designed to **decrease** friction.
5. Name three devices or inventions that are designed to **increase** friction.
6. True or false? A well-oiled machine has no friction. Explain your answer.
7. A box is sliding across the floor from left to right. Which diagram correctly shows the force of friction acting on the box?



8. True or false: Friction makes energy vanish. Explain your answer.
9. True or false: Electronic machines with no moving parts experience friction and get hot because electricity is moving through the wires.

JOURNAL

You Can Count on Friction!

Friction is a part of your daily life.

Write a paragraph telling how the events of your day would not have been possible without friction.

Then, imagine the world suddenly had much more friction than normal. Write a paragraph telling how your day would have been affected.

CHALLENGE

Design a New Shoe!

If it weren't for friction it would be hard to walk! We need to be able to place our feet on a hard surface and push off from it to move forward.

Invent a new shoe that would be suitable for an environment of your choice. For example, you might want to design a shoe for mountain climbing or for walking on the Moon!

Make a sketch of your shoe and write an explanation about the research you did to develop the best design.

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.

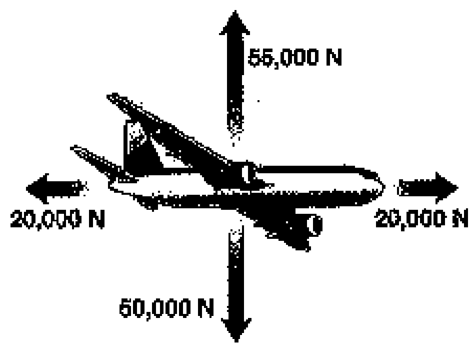
VOCABULARY

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.

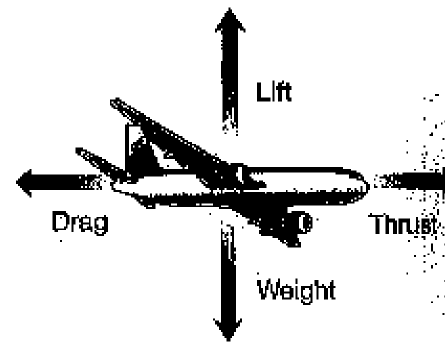


Figure 5.15: *Four forces act on a plane as it flies.*

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.

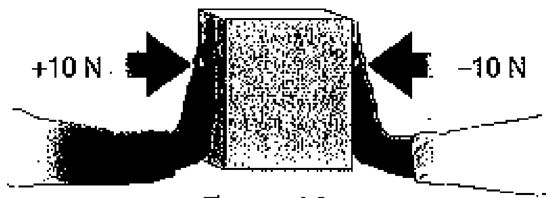
Equilibrium

Net force can be zero or not zero

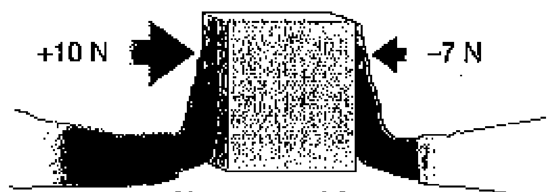
When many forces act on the same object either:

The net force is zero, or

The net force is NOT zero.



Zero net force



Nonzero net force

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.

When the net force is zero . . .

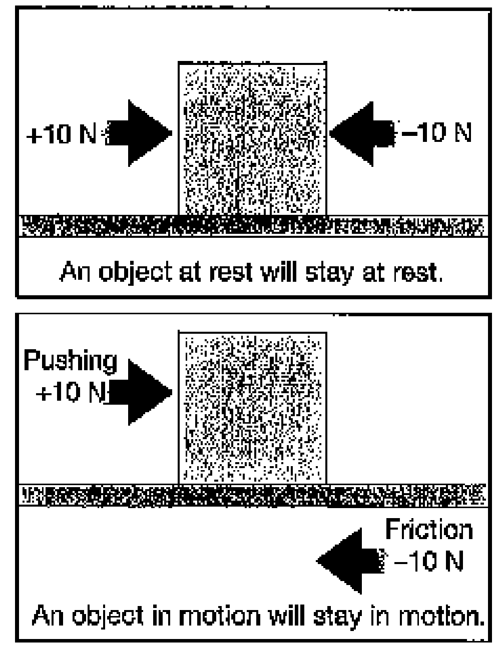


Figure 5.16: *Objects are in equilibrium when the net force is zero.*

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.

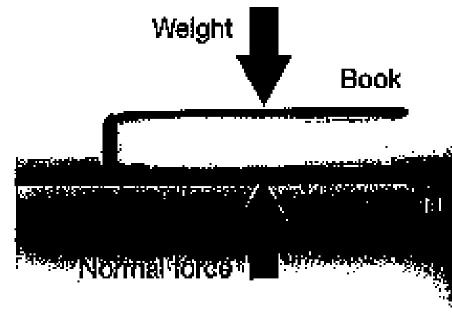


Figure 5.17: *The normal force and the weight are equal in strength and opposite in direction on a horizontal surface.*

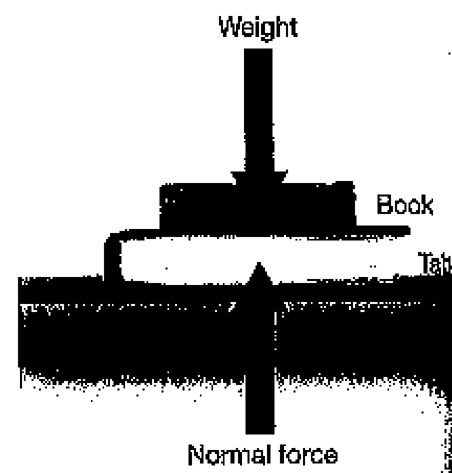


Figure 5.18: *The normal force is greater if a brick is placed on the book.*

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.

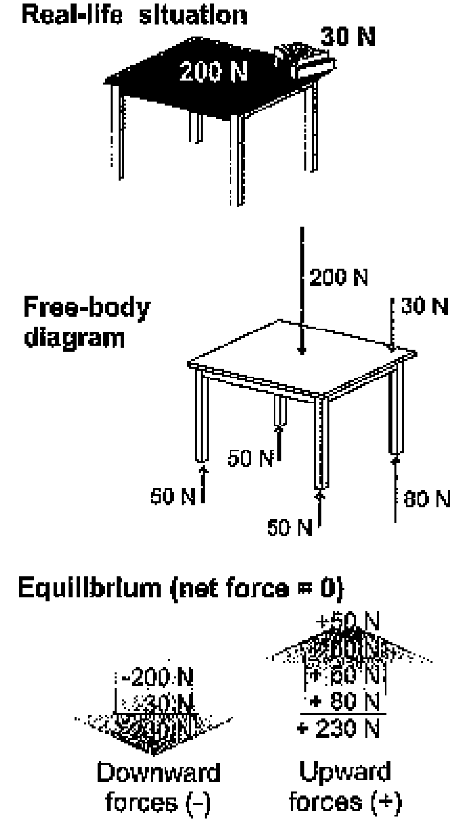


Figure 5.19: *A free-body diagram showing the forces acting on a table that has a stack of books resting on one corner.*

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?

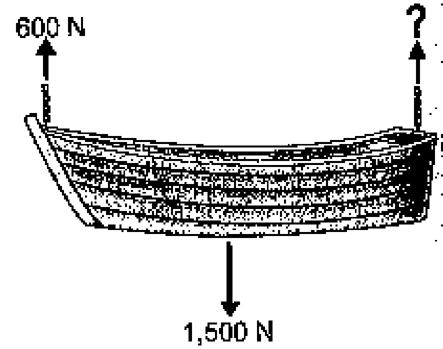


Figure 5.20: *What is the force exerted by the other chain that is supporting the boat?*

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.)

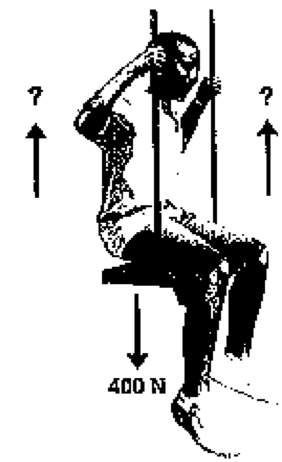


Figure 5.21: *What is the tension force in each rope holding up the swi[ng]*

SOLVE FIRST LOOK LATE[R]

(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?

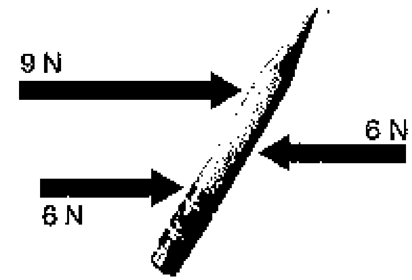


Figure 5.22: *Question 5.*

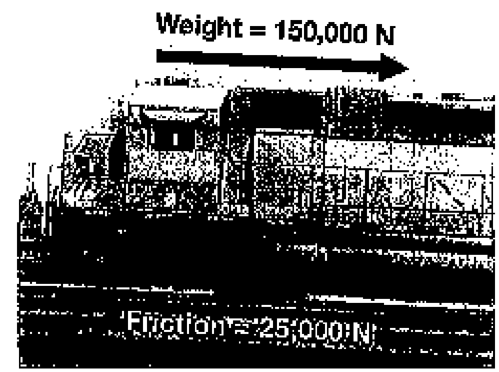


Figure 5.23: *Question 7.*