

# 5.0

Mechanical systems involve machines that are designed to do work efficiently.



Sailors use pulleys and winches to help them raise the sails up the mast.





## ***What You Will Learn***

In this chapter, you will:

- analyze the uses of a variety of machines
- determine the mechanical advantage of a variety of machines
- determine the efficiency of a machine and suggest ways to increase its efficiency

## ***Skills You Will Use***

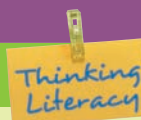
In this chapter, you will:

- manipulate simple machines in order to change their mechanical advantage
- design and construct a mechanism to perform a specified task

## ***Why This Is Important***

Every day you use a variety of mechanisms to perform tasks that require work to be done. Understanding the simple machines that make up these mechanisms allows you to complete the tasks efficiently.

## ***Before Reading***



### **Predict-Read-Verify**

Topics introduced in this chapter include:

- Simple Machines
- Ideal Mechanical Advantage
- Efficiency
- Increasing a Machine's Efficiency

Write down each of these topic titles and discuss what you think the topic means. Make a prediction about what you will learn.

### **Key Terms**

- |                  |                  |
|------------------|------------------|
| • mechanism      | • inclined plane |
| • simple machine | • screw          |
| • lever          | • wedge          |
| • fulcrum        | • efficiency     |
| • pulley         | • wheel and axle |



## 5.0 Getting Started



**Figure 5.1** A mountain bike has several different moving parts.



**Figure 5.2** The gear-change lever on a mountain bike

Modern mountain bikes, like the one shown in Figure 5.1, allow the rider to climb steep hills and travel rough trails faster than by walking or running. But did you ever consider a mountain bike as a machine? A machine is any device that helps us do work.

A mountain bike is a mechanism. A **mechanism** is made up of several different types of machines that work together to perform a specific function. The bike is a complex mechanical system that is made up of many simple machines. A **simple machine** is a machine that requires the application of a single force to do work. You need only the pushing force when using an inclined plane (ramp) to move a cart into a delivery truck. Therefore, a ramp is a simple machine. Similarly, a lever uses only a single force to pry open a lid. Therefore, it is also a simple machine. Figure 5.2 shows the gear lever on a bicycle. Many different parts on the mountain bike move in different ways. Therefore, the bike consists of many simple machines.

A gear is a wheel with teeth around the edge that interacts with another toothed part of a device to change the speed,

direction, or force of a transmitted motion. The sprocket or gear on the back wheel represents one of the bike's simple machines (Figure 5.3). At this location, the force and motion of the chain are transferred to the wheel. Mountain bikes allow the rider to change the distance between the chain and the axle. This is commonly called "switching gears." When the chain is mechanically moved from one sprocket to another, the mechanical advantage changes. When the rider needs to climb a steep hill, the chain is moved to a larger sprocket, increasing the mechanical advantage. When the rider needs less output force but wants to travel faster, the chain is moved to a smaller sprocket.

Simple machines (such as a ramp) and mechanisms (such as the mountain bike) both use forces to transfer energy. Machines are designed to transfer this energy as efficiently as possible. In this chapter, you will study several simple machines and their operation.



**Figure 5.3** The mechanical advantage can be changed by moving the chain to different sprockets.

## B23 Quick Lab

### Locating Simple Machines on a Mountain Bike

A mountain bike is a mechanism that is made up of several simple machines. Different parts of the bike produce different kinds of motions. By analyzing where you find movement in the bike, you are identifying locations where a simple machine may exist.

#### Purpose

To find simple machines on a bicycle

#### Materials & Equipment

- bicycle
- pencil and paper

#### Procedure

1. As accurately as possible, make a sketch of a mountain bike.
2. On your sketch, draw circles around the locations on the bike where parts can move. These are the locations of simple machines.
3. Compare your diagram with a classmate's and discuss any differences. Using a different coloured pen or pencil, add any locations of simple machines that are different from those on your diagram.

#### Questions

4. How many locations of simple machines are on your diagram?
5. Were you surprised by the number of locations of simple machines on a bicycle?
6. Choose one of your simple machine locations. Describe the effect on the bike if that simple machine were not allowed to move.



# 5.1

## Simple Machines and Mechanisms

**Here is a summary of what you will learn in this section:**

- Six types of simple machines are: lever, pulley, wheel and axle, inclined plane, screw, and wedge.
- Levers can be classified into three categories: first-class levers, second-class levers, and third-class levers.
- The ideal mechanical advantage of simple machines can be determined without measuring the input and output forces.
- Two or more simple machines that operate together form a mechanism.



**Figure 5.4** Pyramids at Giza in Egypt. The Great Pyramid is the one in the middle. Notice how tiny the people are in the lower left!

The Great Pyramid of Giza, shown in Figure 5.4, was the tallest building on Earth until the 1300s. Built over 4500 years ago, the 150-m-high pyramid is still considered one of the Seven Wonders of the World. It took 20 years to assemble the 2.3 million blocks that were placed, one by one, to form this magnificent building. The granite and limestone blocks had masses between 1000 and 35 000 kilograms.

### B24 Starting Point

Skills **A** **C**



### Choose a Simple Machine

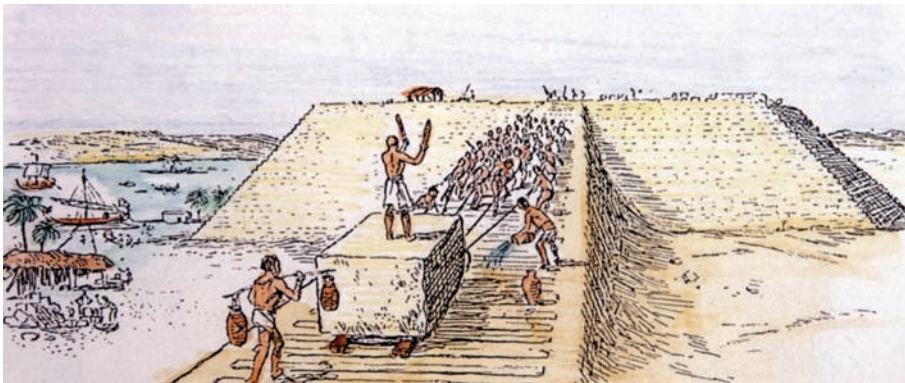
The following situations all require work to be done on an object. For each situation, suggest a tool, device, or machine that could be used to do the work.

- lifting a car to change a tire
- removing a lid from a can of paint
- undoing a tight bolt

- splitting a log for firewood
- moving a car from the lower level of a parking garage to a higher level
- raising a bucket of water in a well

Compare your list with another student's list. Did you both choose the same machine or device for each task?

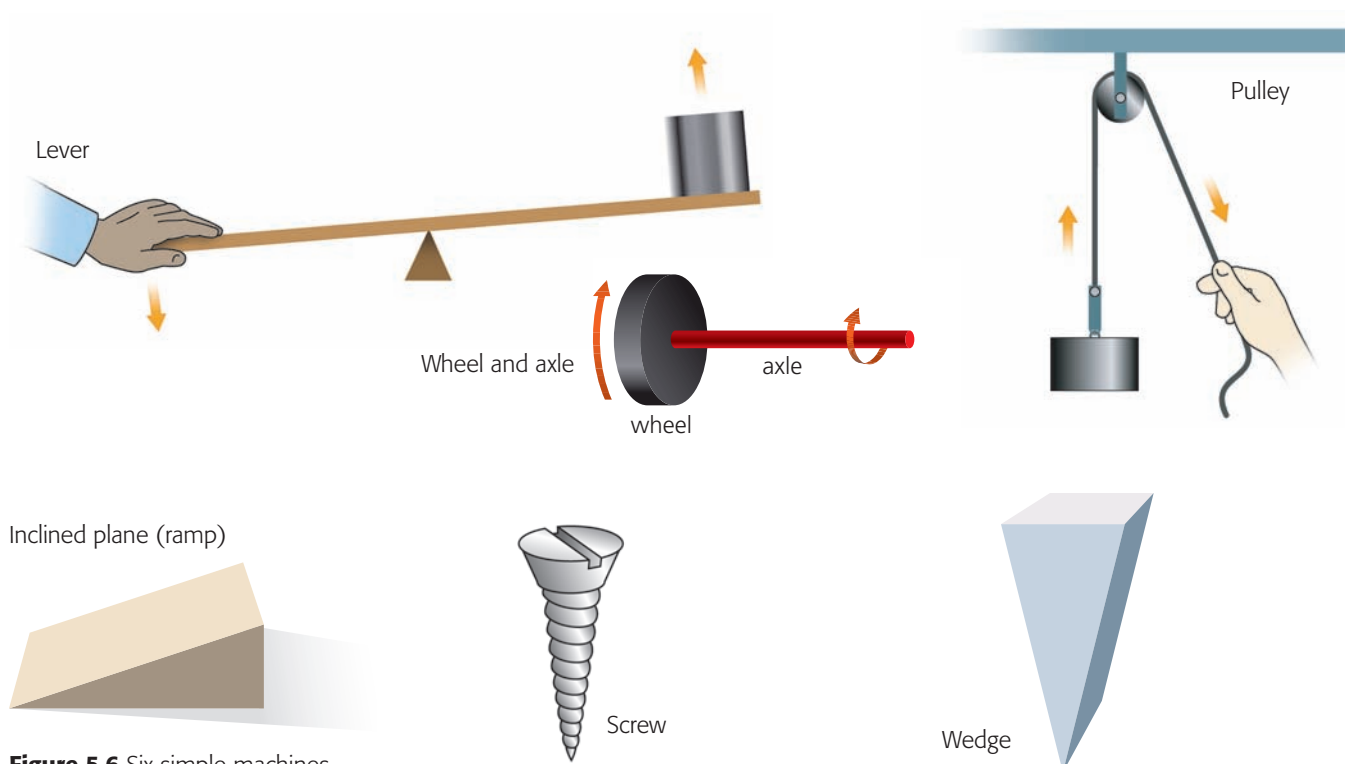
The biggest question is, how did the Egyptians move these massive blocks of stone into place? Although there are no formal records, scientists believe that the early Egyptians used several simple machines. Long inclines (ramps) were built to raise the huge blocks. Some archeologists believe that the blocks were pulled up the ramps on skids (Figure 5.5). Others think that logs were placed under the blocks, like wheels under a cart, when they were pulled up the ramp. The workers set the blocks in place using long wooden and bronze levers.



**Figure 5.5** The massive blocks used to build this pyramid were positioned using simple machines.

## Six Simple Machines

All machines, regardless of how complex, are made up of at least one of six simple machines, which are shown in Figure 5.6



**Figure 5.6** Six simple machines

## To Predict or to Infer?

At the start of this chapter, you made a prediction about what you think you will learn based on what you already know. As you read, you will be able to confirm whether or not your prediction was correct.

Making an inference is related to predicting. As you read, you add what you already know to clues in the text. Making an inference, however, involves the reader using these clues to form a

logical conclusion. This conclusion may not be directly confirmed until the end of the text.

Draw a three-column chart labelled "It Says," "I Say," and "And So" to help you form inferences as you read Section 5.1. What inferences can you make based on the section title? What inferences can you make about the ancient Egyptians?

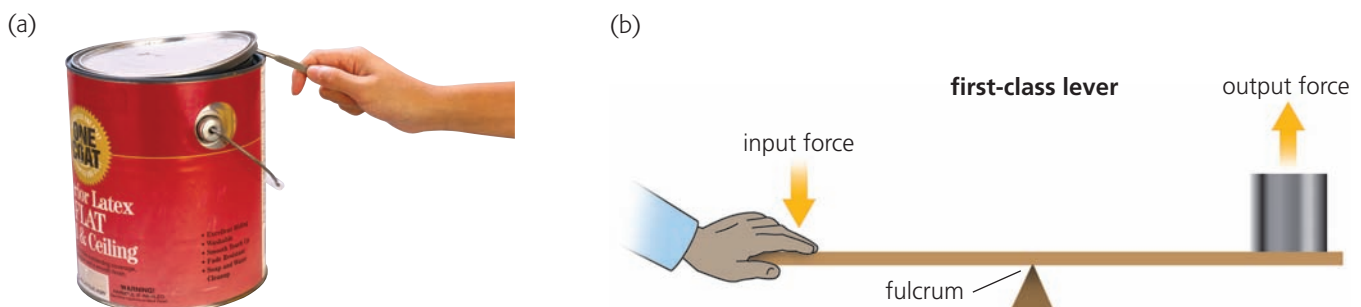
## Levers

If you have ever used a rake, played on a teeter-totter, or swung a baseball bat, you have used a lever. A **lever** is a rigid bar that is supported at one point. This point on the lever is called the **fulcrum**. There are three classes of levers, classified by the locations of the fulcrum, the input force, and the output force.

### Three Classes of Levers

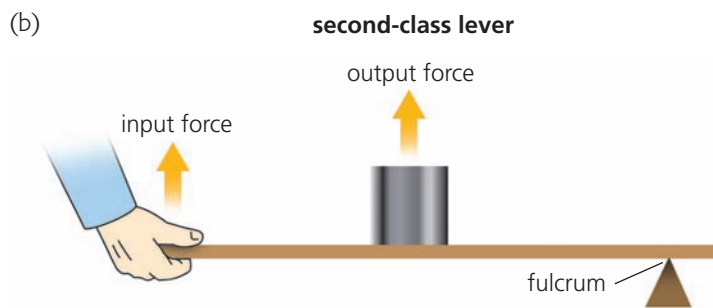
Using a pry bar to remove the lid of a paint can is an example of a first-class lever (Figure 5.7(a)). The fulcrum is the part of the pry bar that is touching the rim of the can. That part of the pry bar is stationary; it does not move. The input force is at your hand, pushing down on the pry bar handle. The output force is at the tip of the pry bar, pushing the lid of the paint can upward. A **first-class lever** always has the fulcrum between the input and output forces (Figure 5.7(b)). As well, the output force is always in the opposite direction to the input force.

**Figure 5.7** When used to open a paint can, a pry bar (a) is an example of a first-class lever, which has the fulcrum between the input and output forces (b).





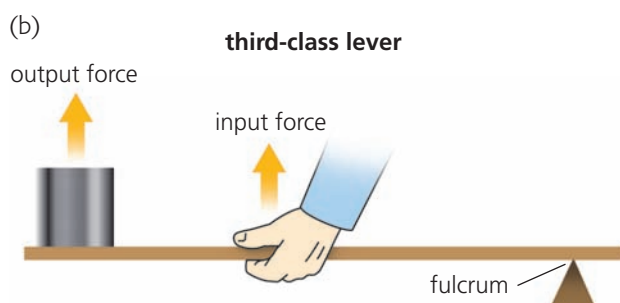
Removing the cap from a soft-drink bottle requires a different class of lever, called a **second-class lever** (Figure 5.8(a)). In this situation, the fulcrum is the very end of the opener that remains in contact with the bottle cap. The force used to open the cap, the output force, is between the fulcrum and the input force (Figure 5.8(b)). In a second-class lever, the input and output forces are in the same direction.



**Figure 5.8** A bottle opener (a) is an example of a second-class lever, which has the output force between the fulcrum and the input force (b).

Using a garden rake or shooting a puck with a hockey stick are examples of the **third-class lever** (Figure 5.9(a)). If you hold the top of the rake stationary with your left hand (the fulcrum) and move the rake with the right, your right hand is the input force. The head of the rake applies an output force to the leaves. The third-class lever has the input force between the fulcrum and the output force, and the input and output force are in the same direction (Figure 5.9(b)).

A third-class lever always produces a mechanical advantage less than 1. That is, the output force is always less than the input force. Instead, a third-class lever is useful because the distance and speed of the output end of the lever are greater than at the input end. Swinging a baseball bat or hockey stick are all examples of creating speed with a third-class lever.



**Figure 5.9** A garden rake is an example of a third-class lever, which has the input force between the fulcrum and the output force.



## Ideal Mechanical Advantage of a Lever

As with all machines, the mechanical advantage can be calculated by dividing the output force by the input force. But you would have to measure these forces by conducting an experiment. Sometimes it is enough to find the ideal mechanical advantage. When the amount of friction is relatively small, calculating the ideal mechanical advantage can provide a good approximation of the machine's actual mechanical advantage. You do not have to conduct an experiment to measure the forces. Remember from Chapter 4 that the ideal mechanical advantage assumes that no friction is involved in the transfer of energy using forces.

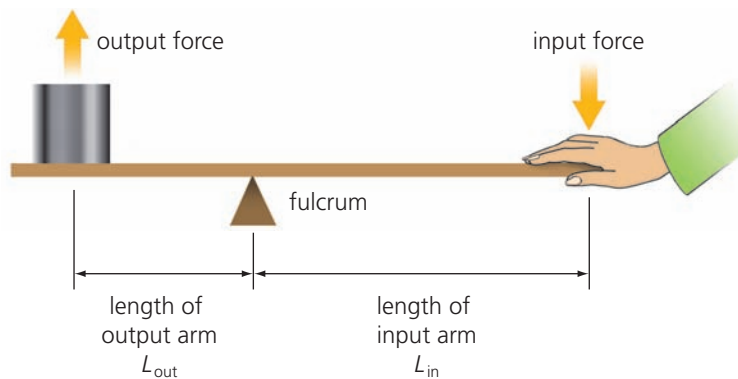
The ideal mechanical advantage (IMA) of a lever can be calculated by dividing the length of the input arm ( $L_{in}$ ) by the length of the output arm ( $L_{out}$ ).

$$\text{Ideal Mechanical Advantage} = \frac{\text{length of input arm}}{\text{length of output arm}}$$
$$\text{IMA} = \frac{L_{in}}{L_{out}}$$

### Suggested Activity •••••

B27 Inquiry Activity on page 141

The length of the input arm is the distance between the location of the input force and the fulcrum. The output arm length is the distance between the fulcrum and the output force (Figure 5.10).

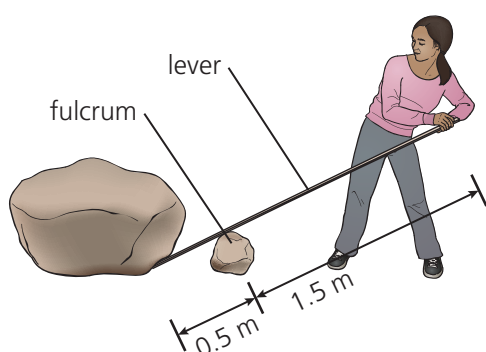


**Figure 5.10** The ratio of the length of the input arm ( $L_{in}$ ) to the length of the output arm ( $L_{out}$ ) is the ideal mechanical advantage of a lever.

For example, Jasmine tries to lift a rock using the lever shown in Figure 5.11. What is the ideal mechanical advantage of this lever?

$$\begin{aligned} \text{IMA} &= \frac{L_{\text{in}}}{L_{\text{out}}} \\ &= \frac{1.5 \text{ m}}{0.5 \text{ m}} \\ &= 3.0 \end{aligned}$$

This lever has an ideal mechanical advantage of 3.0.



**Figure 5.11** When the length of the input arm is greater than the length of the output arm, that lever has an ideal mechanical advantage greater than 1.

### Take It Further

Levers come in three types: first-class, second-class, and third-class. The human body contains each of these three types of lever. Give an example of a location in the human body for each of these three types of lever. Make a sketch of the fulcrum and forces for each example. Begin your search at ScienceSource.

## B26 Learning Checkpoint



### Three Classes of Levers

Figures 5.12, 5.13, and 5.14 each display a common lever. Do the following for each figure:

1. Sketch the lever involved.
2. Label the fulcrum, input force, and output force.
3. Identify the lever as a first-class, second-class, or third-class lever.



**Figure 5.12**



**Figure 5.13**



**Figure 5.14**

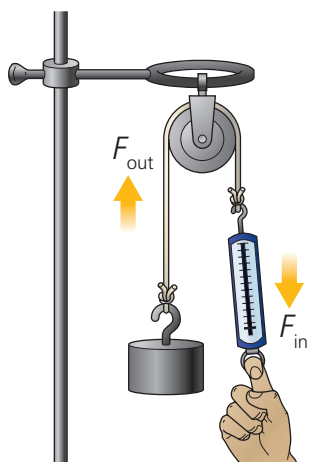




**Figure 5.15** Bones and joints act as levers.



**Figure 5.16** A fixed pulley



## Human Levers

Many movements of the human body can be explained by comparing them with levers. For example, levers give us the ability to throw a ball (Figure 5.15). The solid rod of a lever can be compared to the bones in your forearm. When a person throws a ball overhand, the elbow acts as the fulcrum of a first-class lever and the triceps muscle applies the input force. The output force is the force that the hand applies to the ball. Since the length of the input arm (the distance between the elbow and the triceps muscle) is less than the length of the output arm (the distance from the elbow to the ball), the mechanical advantage when throwing a ball is less than 1.

The process of throwing a ball also involves other levers in the human body, such as at the shoulder and wrist.

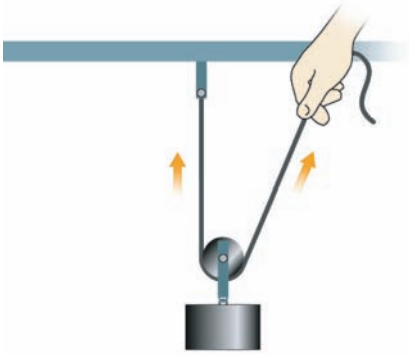
## Pulleys

If you have ever raised a flag on a flagpole or hung clothes on a clothesline, you have used a pulley. A **pulley** consists of a grooved wheel with a rope or cable looped around it (Figure 5.16). The pulley is free to spin. A pulley can change the direction of the force or increase the output force, depending on whether the pulley is fixed or movable.

Fixed pulleys change only the direction of the force. When the input force is applied downward on the rope, the output force is in the upward direction (Figure 5.17). Since the output force is the same size as the input force, a fixed pulley has an ideal mechanical advantage of 1.

If one end of the rope is fixed and the pulley is allowed to move, you have a movable pulley. The movable pulley in Figure 5.18 is supported by the rope at two locations. At each of these locations, the tension in the rope applies an upward force on the pulley. Each segment of rope that applies a force on the pulley is considered a support rope. If you pull the rope with an input force of 5 N, the rope applies this force to the movable pulley in two locations. Therefore, the output force is 10 N. This gives an ideal mechanical advantage of 2.

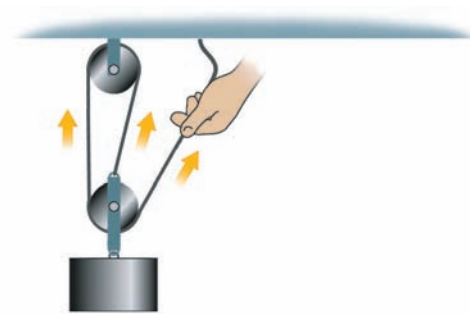
**Figure 5.17** A fixed pulley showing the input and output forces



**Figure 5.18** This movable pulley has two support ropes and therefore an ideal mechanical advantage of 2.

## Ideal Mechanical Advantage of a Pulley System

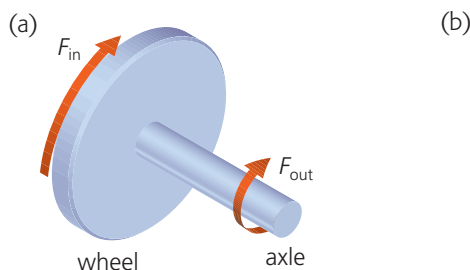
The ideal mechanical advantage of a pulley system is equal to the number of support ropes. A combination of fixed and movable pulleys can produce various mechanical advantages. Figure 5.19 shows a pulley system with one fixed and one movable pulley. By counting the number of support ropes, you find that the ideal mechanical advantage for this pulley system is 3.



**Figure 5.19** This pulley system has an ideal mechanical advantage of 3, since it has three support ropes.

## Wheel and Axle

Could you tighten a screw with a screwdriver that had no handle? The screwdriver handle is part of a simple machine called a wheel and axle. The **wheel and axle** consists of a shaft or axle that is attached to a larger disk, called the wheel (Figure 5.20(a)). When you use a screwdriver to tighten a screw, the handle is the wheel and the shaft is the axle (Figure 5.20(b)). Doorknobs and the pedals on your bicycle are also examples of wheels and axles.



**Figure 5.20** (a) A wheel and axle.  
(b) A screwdriver is an example of a wheel and axle.



## Ideal Mechanical Advantage of a Wheel and Axle

Both the wheel and the axle rotate around the centre of the axle. If an input force acts on the wheel, then the output force provided by the axle produces an ideal mechanical advantage greater than 1. This is because the input force is farther from the centre of the axle than the output force is. Using a screwdriver to turn a screw is an example of using a wheel and axle to increase output force. The input force acts on the handle, and the output force is at the head of the screwdriver.

Sometimes the input force is applied to the axle. The wheels on a car or bicycle turn because of the input force applied to the axle (Figure 5.21). In this case, the mechanical advantage is less than 1 since the input force is closer to the centre of the axle than the output force is.

If the input force is applied to the axle, the ideal mechanical advantage can be calculated by dividing the radius of the axle ( $r_a$ ) by the radius of the wheel ( $r_w$ ).

$$\text{Ideal Mechanical Advantage} = \frac{\text{radius of the axle}}{\text{radius of the wheel}}$$

$$\text{IMA} = \frac{r_a}{r_w}$$

If the input force is applied to the wheel, the ideal mechanical advantage can be calculated by dividing the radius of the wheel ( $r_w$ ) by the radius of the axle ( $r_a$ ).

$$\text{Ideal Mechanical Advantage} = \frac{\text{radius of the wheel}}{\text{radius of the axle}}$$

$$\text{IMA} = \frac{r_w}{r_a}$$

For example, the handle of a garden tap of radius 3.0 cm is connected to a shaft of radius 0.50 cm (Figure 5.22). What is the ideal mechanical advantage of this wheel and axle?

$$\begin{aligned} \text{IMA} &= \frac{r_w}{r_a} \\ &= \frac{3.0 \text{ cm}}{0.50 \text{ cm}} \\ &= 6.0 \end{aligned}$$



**Figure 5.21** Since the input force is applied closer to the axle than the output force on the rim, this bike wheel has an IMA less than 1.



**Figure 5.22** When you turn on the tap, you put force on the handle, which is a wheel. This turns the axle, which opens the tap.

## Inclined Planes

Sometimes the force needed to lift an object up a height is greater than we can safely apply. For example, when a hill is too steep for a car to travel in a straight line, a zigzag road is built with a gentler slope (Figure 5.23). A sloping surface on which an object can move is called an **inclined plane**. A ramp (for example, a wheelchair ramp) is another name for an inclined plane. The ramp reduces the force needed to move the wheelchair, but the distance the wheelchair must travel to get to the top of the ramp has increased.



**Figure 5.23** By decreasing the slope of the road, the car travels a greater distance but with less required force.

### Ideal Mechanical Advantage of an Inclined Plane

If you have to lift an object a vertical height, you can use an inclined plane or ramp. While the ramp increases the distance the object must travel, as shown in Figure 5.24, the amount of force you need is less than if you lifted the object straight up. The ideal mechanical advantage of an inclined plane is the ratio of the length of the slope ( $l$ ) to the height of the ramp ( $h$ ).

$$\text{Ideal Mechanical Advantage} = \frac{\text{length of ramp}}{\text{height of ramp}}$$

$$\text{IMA} = \frac{l}{h}$$

For example, an object is raised 1.0 m (vertical distance) by pushing it along a loading ramp 6.0 m long. What is the ideal mechanical advantage of this ramp?

$$\begin{aligned}\text{IMA} &= \frac{l}{h} \\ &= \frac{6.0 \text{ m}}{1.0 \text{ m}} \\ &= 6.0\end{aligned}$$

**Suggested Activity** • .....  
B28 Problem-Solving Activity  
on page 142



**Figure 5.24** An inclined plane allows you to use less force over a greater distance.



## The Screw



**Figure 5.25** A screw is an inclined plane wrapped around a rod.

A **screw** is simply an inclined plane wrapped around a rod (Figure 5.25). This continuous inclined plane, starting at the tip, is called the “thread.” The length of the thread is much greater than the length of the screw. As with the inclined plane, this difference in length gives the screw mechanical advantage. The screw’s thread allows it to penetrate into hard wood with minimal force. Many food jars have threads similar to the screw. The threads on the lid and the top part of a jar hold the lid firmly in place.

## The Wedge

When we use an inclined plane, the object is pushed or pulled along the inclined plane. A **wedge** is an inclined plane that travels through the object or material. For example, a wedge can be used to split firewood (Figure 5.26). The longer and narrower the wedge, the greater its mechanical advantage. Needles, knives, and your front teeth are all examples of wedges.



**Figure 5.26** A wedge is an inclined plane that moves through the object.

## Mechanisms

Many of the machines that you use every day consist of several simple machines working together to perform a task. A **mechanism** is two or more simple machines working together. At the beginning of this unit you learned that a mechanical system is a group of physical parts that interact with each other and function as a whole in order to complete a task. Therefore, mechanisms are mechanical systems. Bicycles and cars are obvious mechanisms. Even simple scissors can be considered a mechanism since they consist of a lever and a wedge (Figure 5.27).



**Figure 5.27** Scissors are a mechanism.

- Measuring
- Controlling variables

## Measuring the Mechanical Advantage of Simple Machines

### Question

What factors affect the mechanical advantage of a lever and an inclined plane?

### Materials and Equipment

- spring scale
- 1.0-kg mass
- wooden board
- metre stick
- support stand
- string

### Procedure

#### Part 1 – The Lever

1. Copy Table 5.1 into your notebook.

**Table 5.1** The Lever

Trial	Length of Input Arm (cm)	Length of Output Arm (cm)	Input Force (N)	Output Force (N)	MA	IMA
1	45	25		9.8		
2	35	25		9.8		
3	25	25		9.8		
4	15	25		9.8		

2. Support a metre stick from a support stand using a string attached to the 50-cm location on the metre stick.
3. Attach a 1.0-kg mass to the 25-cm location (25 cm from fulcrum) and a spring scale to the 95-cm location (45 cm from fulcrum).
4. Measure the force required to slowly lift the mass. Record this input force in Trial 1.
5. By moving the location of the spring scale, repeat steps 3 and 4 for the remaining trials shown in the table.
6. Calculate the mechanical advantage (MA) and ideal mechanical advantage (IMA) for each trial.

#### Part 2 – The Inclined Plane

7. Copy Table 5.2 into your notebook, with space for four trials.

**Table 5.2** The Inclined Plane

Trial	Length of Ramp	Height of Ramp	Input Force (N)	Output Force (N)	MA	IMA
1				9.8		
2				9.8		

8. Stack some books on your table. Using the wooden board, set up a ramp from your desk to the top of the stack of books. Measure the length and the vertical height of the ramp. Record these measurements in Trial 1.
9. Attach your spring scale to the mass at the base of your ramp and slowly pull the mass up the ramp. Record this input force in Trial 1.
10. Lower the height of the ramp and repeat steps 8 and 9. Repeat for a total of four trials.
11. Calculate the mechanical advantage and ideal mechanical advantage for each trial.

### Analyzing and Interpreting

12. Which simple machine produced the largest mechanical advantage?
13. In general, how does the size of the ideal mechanical advantage compare to the mechanical advantage?

### Skill Builder

14. For the inclined plane, which variables in the experiment did you control to ensure that this was a “fair” experiment?

### Forming Conclusions

15. For each of the simple machines, explain what variables can be manipulated to change the mechanical advantage.

## B28 Problem-Solving Activity

Toolkit 3

### SKILLS YOU WILL USE

- Modelling
- Explaining systems

## Best Machine for the Job

### Recognize a Need

Have you ever thought of becoming an engineer? Engineering is the application of science to develop solutions and design structures that are useful to people. For example, you might need to lift a large mass to the top of a skyscraper.

### Problem

Design and construct a mechanism made from simple machines that will move a 1.0-kg mass from the floor to the top of your desk using the smallest input force.

### Materials & Equipment

- spring scale
- various simple machines
- string
- 1.0-kg mass

### Criteria for Success

- The final design must include at least one simple machine.
- The input force must be applied by your hand.
- Your design must allow for continual measurement of the force applied by your hand.
- The mechanism must be able to move the mass from the floor to the surface of the desk in a safe manner.

### Brainstorm Ideas

1. Which simple machines would be best suited for this task?
2. What variables in each machine can you control to maximize the mechanical advantage?
3. What materials will you use?

### Make a Drawing

4. On a single piece of paper, start your sketch by first drawing the floor and the table. Add the starting location of the 1.0-kg mass.
5. Sketch your design for your mechanism. Label the simple machine(s) involved in your design. Your design must show the location of the spring scale used to measure your input force.
6. Be sure to show your drawing to your teacher before going any further.

### Test and Evaluate

7. Construct your mechanism.
8. As you operate your mechanism to move the mass, note the maximum force measured by the spring scale. Record this value.
9. The output force required to lift a 1.0-kg mass is 9.8 N. Calculate and record your mechanism's mechanical advantage.
10. Suggest ways of improving your mechanism's mechanical advantage.

### Communicate

11. Share and compare your design and mechanical advantage with your classmates' results. Did anyone have a similar design? How did their results compare with yours? What do you think is the best design for this problem?
12. Present your findings to the class or in a form suggested by your teacher.



## Key Concept Review

1. Match each photograph below to one of the six simple machines.

(a)



(b)



(c)



2. State the class of lever for each of the levers in the chart. The locations are shown below the chart.

	Location 1	Location 2	Location 3
Lever A	fulcrum	input force	output force
Lever B	output force	fulcrum	input force
Lever C	fulcrum	output force	input force



3. Two ramps of different lengths are used to lift furniture into the same truck. Which ramp requires less force?
4. Explain the difference between a mechanism and a simple machine.

## Connect Your Understanding

5. A metre stick is used as a lever. If the input force is applied at 0 cm and the output force is exerted at 100 cm, what is the ideal mechanical advantage if the fulcrum is at 75 cm?
6. As the mechanical advantage of a simple machine is increased, how does the distance of the input force compare to the distance of the output force?

## Practise Your Skills

7. Draw a simple diagram for the lever involved in the photograph below. On the diagram, label the input force, output force, and fulcrum.

- (a) State the class of lever involved.
- (b) Is the mechanical advantage of this lever greater than 1 or less than 1?



For more questions, go to ScienceSource.



## B29 Thinking about Science, Technology, and Society



## Think Before You Buy

When shopping for a mechanism, how do you decide which one to buy? How do manufacturers try to get you to buy their product?

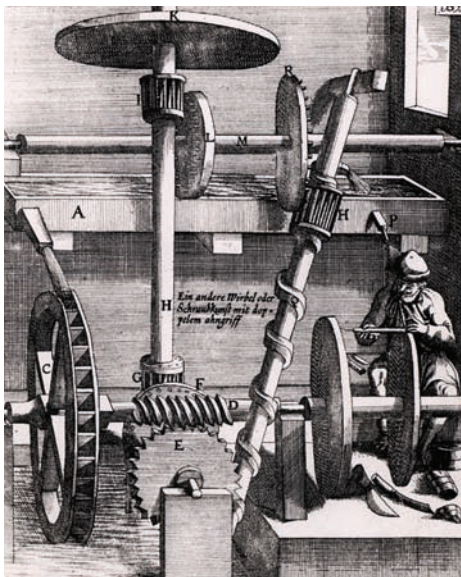
## Consider This

Choose a mechanism that you have recently purchased.

- What did the advertisements say and what images did they use to convince you to buy this product? How do these images attract you (or not) to buy their product?
- List the criteria you used when deciding which mechanism to purchase.

**Here is a summary of what you will learn in this section:**

- The work done by a machine is less than the work put into the machine.
- The efficiency of a machine can be calculated by dividing the output work by the input work.
- A machine's efficiency can be increased by reducing the friction that produces heat.



**Figure 5.28** An attempt at a perpetual-motion machine

Can you imagine a machine that runs forever without using any energy? A perpetual-motion car would run without having to be refilled with gas. Over the years, inventors have tried to invent perpetual-motion machines with no success. Such a machine would break the laws of physics.

Figure 5.28 shows a water-screw perpetual-motion machine from the 1600s. Water in the trough falls and turns the water wheel, which is connected to gears that turn a screw. The turning screw carries the water back up to the trough, and the whole process, in theory, should repeat itself. However, this machine soon comes to a grinding halt.

The gravitational potential energy of the water in the trough cannot provide enough energy to turn the screw to return the same amount of water back to the trough. Some of the water's original stored energy is transformed into other forms of energy, such as heat, that this machine cannot use to lift water.

## B30 Starting Point

Skills **A** **C**



### Work Can Be a Drag

When you lift an object, it gains gravitational potential energy. Regardless of what machine you use to lift the object, the output work ( $W_{\text{out}}$ ) is the same.

#### What to Do

1. Pull a cart slowly up a ramp using a spring scale. Record the amount of force required.
2. Turn the cart over so that the wheels are not touching the incline. Repeat step 1.

#### Consider This

3. Which situation required a larger force? Since the length of the ramp was the same in both situations, which situation required more input work ( $W_{\text{in}}$ )?
4. Both situations provided the same output work ( $W_{\text{out}}$ ). Explain what happened to the extra energy needed with the larger input work ( $W_{\text{in}}$ ).

## Efficiency of Machines

Fuel-efficient cars and energy-efficient light bulbs are common topics in today's society. But what does it mean to be efficient? Perhaps you have been called an efficient worker. This generally means that you get jobs done without wasting time and energy. In science, the efficiency of a machine is determined by analyzing the energies involved.

The **efficiency** of a machine measures the useful work done by the machine compared to the work needed to operate it. **Useful output work** is the work that the machine is designed to perform. For example, a bicycle is designed to move forward. The bicycle's useful output work is determined by measuring the bicycle's forward motion (Figure 5.29). The input work is the work done by the person moving the pedals. For mechanisms such as the bicycle, the useful output work is always less than the input work. But where does the extra energy go?

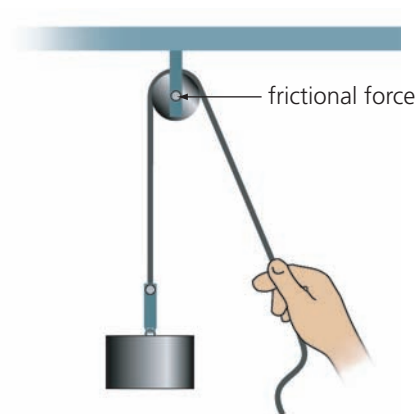
### Work Done by Friction

Whenever a machine is used to do work, parts of the machine are moving. For example, if a pulley is used to lift an object, not only does the object move, but parts of the pulley also move. A force of friction occurs where the pulley wheel rotates on its shaft. Since the force of friction is applied to a distance of motion, work is done by the friction force. Work done by the force of friction transforms input energy into heat when the pulley wheel turns (Figure 5.30). Therefore, extra work must be input into the machine to compensate for the work done by friction. For this reason, the useful output work of a machine is always less than the input work.

Highly efficient machines have less friction and therefore produce less heat from friction. More of the input work is changed into useful output work. An ideal machine would have no friction, and therefore all the input work would be converted to output work. Like the perpetual-motion machine, an ideal machine does not exist. Our current goal is to produce machines and mechanisms that are as efficient as possible, such as the solar-powered car in Figure 5.31 on the next page.



**Figure 5.29** The useful output work of the bicycle is determined by examining the forward motion.



**Figure 5.30** Friction between the wheel and its shaft produces heat when the pulley is used to lift the object.



**Figure 5.31** The University of Waterloo team came fourth in the North American Solar Car Challenge in 2005. The 4000-km race lasted 10 days.



## Calculating Efficiency

To calculate the efficiency of a machine, the useful output work ( $W_{\text{out}}$ ) is divided by the input work ( $W_{\text{in}}$ ). Efficiency is usually expressed as a percentage.

$$\text{Efficiency} = \frac{\text{useful output work (joules)} \times 100\%}{\text{input work (joules)}}$$

$$\text{Efficiency} = \frac{W_{\text{out}} \times 100\%}{W_{\text{in}}}$$

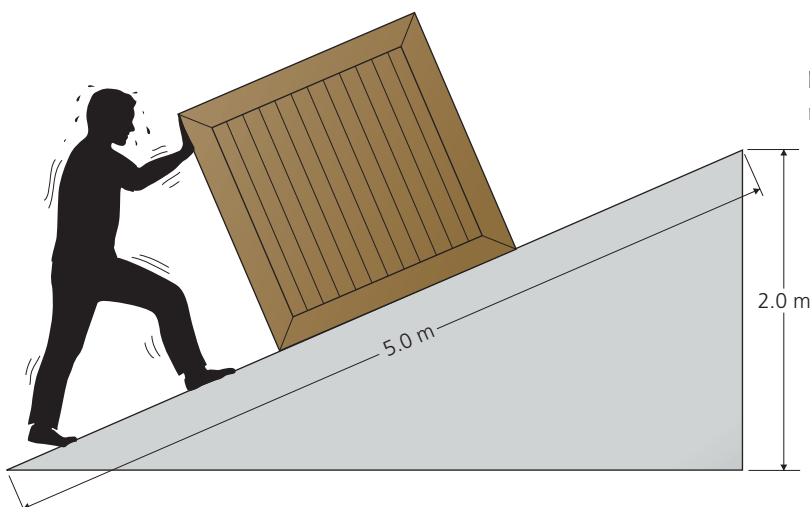
For example, a machine is capable of doing 35 J of work when 50 J of work is put into the machine. What is the efficiency of this machine?

$$\begin{aligned} \text{Efficiency} &= \frac{W_{\text{out}} \times 100\%}{W_{\text{in}}} \\ &= \frac{(35 \text{ J}) \times 100\%}{(50 \text{ J})} \\ &= 70\% \end{aligned}$$

This means that 70% of the work put into the machine goes into doing work that the machine was designed for. The other 30% of the input work goes into other forms of energy.

The efficiency of a machine can also be calculated by measuring the forces and distances. For example, a 500-N crate is moved up a 5.0-m-long ramp (Figure 5.32). What is the efficiency of this ramp if the person pushes with a force of 400 N in order to raise the crate a vertical distance of 2.0 m?

To calculate the efficiency, we must first calculate the useful output work and the input work. Remember from Chapter 4 that  $W = Fd$ .



**Figure 5.32** A 500-N crate is being pushed up the ramp with a force of 400 N.

$$\text{Useful output work} = (500 \text{ N})(2.0 \text{ m}) = 1000 \text{ J}$$

$$\text{Input work} = (400 \text{ N})(5.0 \text{ m}) = 2000 \text{ J}$$

Now we can use this work to calculate the efficiency.

$$\begin{aligned} \text{Efficiency} &= \frac{W_{\text{out}} \times 100\%}{W_{\text{in}}} \\ &= \frac{(1000 \text{ J}) \times 100\%}{(2000 \text{ J})} \\ &= 50\% \end{aligned}$$

This inclined plane is 50% efficient.

This ramp has a mechanical advantage greater than 1, which means that less force is required to lift the crate. Even though less force is required, some of the work done by the person is transformed into heat by the friction between the crate and the ramp. Therefore, the efficiency is not 100%.

**Suggested Activity** •.....  
B32 Inquiry Activity on page 149

### Take It Further

In order to increase the efficiency of a machine, a lubricant can be used to reduce friction. Not all lubricants are liquids like oil. Find out which “dry” materials are used as lubricants. Find an example of a machine in which a dry lubricant is used. Begin your search at ScienceSource.

## B31 Learning Checkpoint



### Calculating Efficiency

You have to lift a mass to a higher location so that the mass gains 800 J of gravitational potential energy. You may use one of three different mechanisms given in the next column to lift the mass. Calculate the efficiency of each mechanism. Which one will you use?

1. You use an electric motor that requires 850 J of energy to lift the mass.
2. You pull the rope of a pulley, which is attached to the mass, a distance of 6.0 m with a force of 150 N.
3. You push the mass 10 m up a ramp with a force of 140 N.

**Table 5.3** The Efficiencies of Some Common Mechanisms

Mechanism	Efficiency (%)
Electric generator	99
Olympic track bike	98
Mountain bike	85
Hybrid-diesel car	45
Electric car	44
Hybrid-gasoline car	36
Conventional gas-powered car	22
Solar cell	10

## The Efficiency of Common Mechanisms

When a mechanism does work, its energy is transformed from one form to another or transferred from one object to another. A car transforms the chemical energy stored in its fuel into several other forms of energy, such as kinetic energy, sound energy, light energy, and thermal energy. Since the main purpose of a car is transportation, the useful output work of the car would be the work done to provide motion (kinetic energy).

We can measure the efficiency of any mechanism that transfers energy. Table 5.3 gives the efficiencies of some common mechanisms.

## How to Increase Efficiency

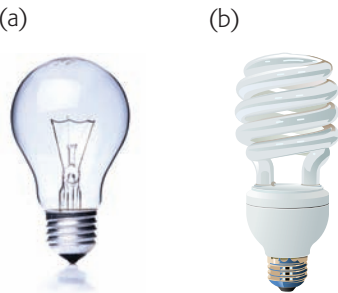
The efficiency of any machine is not 100 % because some of the input work is used to compensate for the work done by friction. When you use a pulley, you may hear the pulley squeak (sound energy) and the pulley wheel may become warm (heat). These result from the work done by friction. If you reduce the frictional force, you increase the efficiency of a machine. The best way to reduce friction is to add a lubricant, such as grease or oil, to any surfaces that rub together.

Lubricants fill the gaps between the two surfaces, making it easier for those surfaces to slide past each other. Because water is also a good lubricant, wet floors are more slippery than dry floors (Figure 5.33).

For some devices, the thermal energy produced during the energy transfer cannot be decreased by a lubricant. A good example is an incandescent lamp, which operates at 175°C (Figure 5.34). At this temperature, only 5 % of the electrical energy is transformed into light energy. The rest becomes heat. Lubricating the filament of the lamp would not increase its efficiency. Compact fluorescent lamps (CFLs) are designed to operate at a much lower temperature, around 30°C. At this temperature, less electrical energy is converted to heat. Therefore, the CFL has a higher efficiency than traditional incandescent lamps.



**Figure 5.33** Water, like oil and grease, acts like a lubricant to decrease the amount of frictional force.



**Figure 5.34** (a) Incandescent light bulb, (b) Compact fluorescent light bulb



- Initiating and planning
- Evaluating information

## Increasing Efficiency

No machine is 100% efficient since extra work must be input to the machine to compensate for the work done by friction. To increase the efficiency of a machine, you must decrease the amount of friction.

### Question

What method will increase the efficiency of a simple machine, and by what amount is the efficiency increased?

#### Materials & Equipment

- spring scale
- inclined plane
- ruler
- mass
- material or process that will reduce friction

### Hypothesis

Write a hypothesis about how the method you will use to reduce friction will change the efficiency of the simple machine.

### Procedure

#### Part 1 – Measuring Efficiency

1. Copy Table 5.4 into your notebook. Give it a title.

Table 5.4

Output Force (N)	Output Distance (m)	Output Work (J)	Input Force (N)	Input Distance (m)	Input Work (J)	Efficiency (%)

2. Stack several books on your desk. Place the mass on your desk at the base of the stack. Using a spring scale, measure the force required to lift the mass straight up. Record this as the output force.
3. Using a ruler, measure the height from the desk to the top of the books. Record this distance as the output distance.

4. Calculate the work required to move the mass from the desk to the top of the stack of books. Record this value as the output work.
5. Place an inclined plane from the desk to the top of the stack of books. Using the spring scale, measure the force required to slide the mass up the incline. Record this value as the input force. Measure the length of your incline and record this as the input distance.
6. Calculate the work required to slide the mass up the incline to the top of the stack of books. Record this value as input work.
7. Calculate the efficiency of this inclined plane.

#### Part 2 – Increasing Efficiency

8. Suggest a process or material that you think will increase the efficiency of your inclined plane. Be sure to get your teacher's approval before going any further.
9. Copy Table 5.4 into your notebook. The values of output force, output distance, and output work are the same as in Part 1. Give this new table a title.
10. Apply your approved changes to the inclined plane and repeat steps 5–7.

### Analyzing and Interpreting

11. Did your material or method increase the efficiency by as much as you expected?
12. Suggest what you might have done differently in order to increase the efficiency even more.

### Skill Builder

13. Calculate the amount of heat produced in both Part 1 and Part 2.

### Forming Conclusions

14. Answer the question at the beginning of this activity.

## Key Concept Review

1. Explain why a machine or a mechanism cannot have an efficiency of 100 %.
2. If the efficiency of a machine increases, what happens to each of the following? (Use the words “increases,” “decreases,” or “stays the same” to describe the changes.)
  - (a) input work
  - (b) useful output work
  - (c) friction
  - (d) mechanical advantage
3. What is the mathematical relationship between efficiency, input work, and useful output work?
4. Explain how a lubricant affects the efficiency and the frictional forces of a machine.

## Connect Your Understanding

5. A student does 25 J of work on the handle of a pencil sharpener. If the pencil sharpener does 20 J of work on the pencil, what is the efficiency of the sharpener?
6. A force of 900 N pushes a wedge 0.10 m into a log. If the work done on the log is 50 J, what is the efficiency of the wedge?

## Practise Your Skills

7. Use the data below to rank machines A, B, and C from:
  - (a) highest to lowest mechanical advantage
  - (b) highest to lowest efficiency

Machine	Input Force (N)	Input Distance (m)	Output Force (N)	Output Distance (m)
A	5.0	10	20	2.0
B	10	25	50	3.5
C	20	6.0	27	4.0

For more questions, go to ScienceSource.


**B33** *Thinking about Science, Technology, and Society*


## Ontario's Bright Idea

The Ontario government has decided to ban the sale of incandescent light bulbs by 2012. It is estimated that by replacing the incandescent bulbs to the more efficient compact fluorescent lights (CFLs), Ontario will save enough energy each year to power 600 000 homes.

## Consider This

With a small group or the whole class, discuss statements 1 and 2. Then answer question 3 by yourself.

1. Switching to CFLs will have both an economic and an environmental impact on Ontario.
2. Switching to CFLs will have both positive and negative impacts on Ontario.
3. Do you agree or disagree with the government's decision? Give reasons for your answer.

## Mechanical Engineer



**Figure 5.35** Some mechanical engineers design roller coasters for a living.

Are you fascinated with building things and with taking things apart to see how they work? Do you like solving puzzles? Would you like to invent a machine that is used by people all over the world? If you answered yes to any of these questions, perhaps you should consider becoming a mechanical engineer. Mechanical engineers use science and mathematics to design mechanical systems that meet societal and consumer needs. These mechanical systems include toys, cars, roller coasters, elevators, spacecraft — basically anything that moves.

Much of a mechanical engineer's work is designing and developing new mechanical systems. This process can usually be broken into four major steps. First, mechanical engineers must fully understand the societal or consumer requirements for the system they are developing. The second step is to design and test the various components of the product. Then, the components are integrated into the final design. The final step is to evaluate the effectiveness of the complete mechanical system. This final

evaluation involves cost, reliability, safety, and impact on the environment.

Once these new systems are being used, mechanical engineers often supervise their operation. This may include supervising production in factories, determining the causes of component failure, or doing tests to make sure the system is operating efficiently.

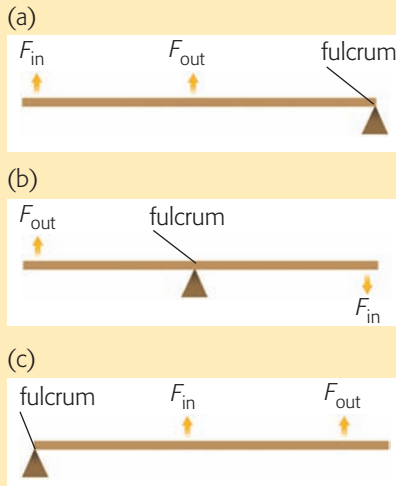
Mechanical engineers require a good background in mathematics, physics, and chemistry. Two of the units in this textbook, *Systems in Action* and *Fluids*, are important if you decide to become a mechanical engineer. After high school, you will go to university to obtain a degree in mechanical engineering, or to college to become an engineering technician.

Mechanical engineers are hired by large corporations, government agencies, and engineering companies. These companies are looking for people who are “team players.” Most engineering projects require the engineers to work with groups of clients, technologists, and other engineers. For this reason, engineers must have great communication and leadership skills.

### Questions

1. What is the job description of a mechanical engineer?
2. Companies that hire mechanical engineers are looking for people who will be “team players.” In your opinion, what characteristics should you have to be considered a “team player”?
3. Which two units in this textbook are closely related to the study of mechanical engineering?





Question 3

## After Reading

Thinking  
Literacy

## Making Connections

At the beginning of this chapter, you predicted what you might learn about simple machines, ideal mechanical advantage, and efficiency. How does the information you have read add to or change what you predicted about these topics?

You have also learned about making inferences. How is inferring the same as and different from predicting? Why might a writer give only essential details on a topic and expect the reader to infer meaning from this information? Share your ideas with the class.

## Key Concept Review

1. Define “simple machine.” *k*
2. Give an example each of a simple machine and a mechanism. *a*
3. Classify each of the levers in the illustration on the left as first-, second-, or third-class. *k*
4. For which class(es) of lever(s) are the input force and the output force *k*
  - (a) in opposite directions?
  - (b) in the same direction?
5. Describe the ideal mechanical advantage and the direction of the input and output forces for a fixed pulley. *k*
6. How does the output work compare to the input work for a machine that has an efficiency *k*
  - (a) equal to 100%?
  - (b) less than 100%?

## Connect Your Understanding

7. To increase the mechanical advantage of a lever, should you increase or decrease the length of the output arm? *a*
8. Pedro and Brittany design a mechanical device that will move desks from one classroom to another on the floor above. They measure the forces and distances and calculate the input and output work. If their calculations show that the input work equals the output work, is their calculation correct? Explain. *a*
9. If you did Activity B23, you sketched locations on a mountain bike that involved simple machines. Using that sketch, label the type of simple machine at each location. *t*
10. A mechanical system is used to pull a tarp over a grass tennis court. On a clear, sunny day, the efficiency of the system is 55%. After a rainstorm, the efficiency is measured to be 65%. Explain why there is a difference in the efficiencies. *a*

11. Each photograph on the right shows a common tool. Identify the type of simple machine each tool represents. **a**

## Practise Your Skills

12. Plan an experiment to measure the ideal mechanical advantage of a three-hole punch. **t**
- (a) What materials would you need?
  - (b) What procedure would you use?
13. Calculate the IMA of a lever whose input force is applied 3 m from the fulcrum and whose output force is 0.5 m from the fulcrum. **t**
14. A ramp that is 5 m long is used to raise an object 2 m vertically. Find the IMA of this ramp. **t**
15. Using one or two pulleys, draw a mechanical system that has: **t**
- (a) an  $\text{IMA} = 2$
  - (b) an  $\text{IMA} = 3$
16. The handle of a screwdriver has a radius of 3 cm. If the shaft of the screwdriver has a radius of 0.5 cm, what is the IMA of the screwdriver when used to tighten a screw? **t**
17. Wei uses a pulley system to lift a box. She pulls the rope a distance of 3 m, using a force of 50 N. If the work done on the box is 120 J, what is the efficiency of the pulley system? **t**



Question 11

## Unit Task Link

In your Unit Task, you will design, construct, and test a mechanical system that uses only the energy stored in a spring-bar mousetrap. The mousetrap machine must have a function other than catching mice. What simple machines might you use in your project? How can you ensure that your design has maximum efficiency?

## B34 Thinking about Science, Technology, and Society



### Building a Modern Pyramid

The ancient Egyptian pyramids, like those shown in Figure 5.4 on page 130, were built over 4500 years ago. Archeologists believe that the workers mainly used ramps and levers when building them.

Suppose you wanted to build a similar pyramid using modern technology.

### Consider This

In small groups or as a class, discuss the following questions.

1. What modern machines do you think would be used in the construction of the pyramid?
2. What developments in science and technology have resulted in these modern machines?