Check and Reflect

1. What is the difference between a simple and a complex machine?
2. What improvements have been made to bicycle designs over the last century?
3. a) Your body is made up of several simple machines that help you move. Identify three parts of your body that act as simple machines. Identify the kind of machine for each one and explain what it does.

   b) What parts of your body act as linkages?
4. Picture yourself riding a bicycle in a race. Describe how energy is transferred from your body to the bicycle wheels.
5. What are gears? How are they used?

Try This at Home — **Activity**

How Many Machines Are in Your Home?

You have lived with machines all of your life, so you may not be aware of how many machines you depend on for comfort, security, and convenience. The machines you have in your home help you and your family do many jobs—even when you're not there!

- Make a list of all the machines that you can think of in and around your home. Some machines may not be obvious. Remember that a machine is any device that moves an object or transfers energy.
- Next to each machine in your list, describe the task that the machine performs.
- Identify the source of energy for each machine in your list. What source of energy do most of the machines use?
- On a typical school day, which of these machines do you use or does someone use to help you? Write a short story describing what your day would be like if you didn't have any of these machines. Would you be able to do the same things? How would you do them?

SECTION REVIEW

Assess Your Learning

1. a) How can you determine if a device is a simple or a complex machine?
   b) Use your answer to question (a) to determine if your body is a simple or a complex machine.
2. Why does a car have a transmission but a bicycle doesn't?
3. Explain how using levers, gears, or other ways of linking components improves the operation of the following devices:
   a) scissors
   b) bicycle
   c) eggbeater
4. Describe three jobs that depend on the use of machines. List the type of machine(s) used with each job.
5. Look at the machine in Figure 1.30, and then answer the questions below.
   a) Is this device a simple or complex machine? Explain your answer.
   b) What do you think the source of energy is for this machine? How do you know?
   c) Draw a simple sketch of a similar machine in your notebook. On your sketch, show how energy is transferred through the machine. Label any levers, gears, or belt drives.
   d) Do you think this device could work in real life? Why or why not?

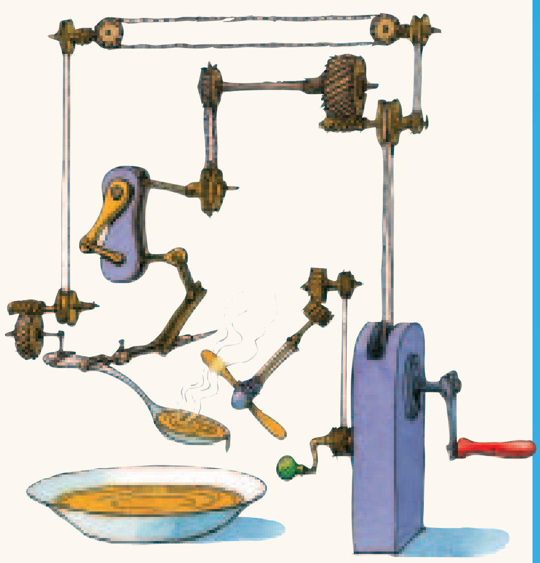

Figure 1.30 Question 5

Focus On SCIENCE AND TECHNOLOGY

The products of technology are devices, systems, and processes that meet given needs and wants. For example, a CD player is a system of devices that work together to provide us with entertainment or educational information. Think back to the information you learned and the activities you did in this section.

1. Describe two devices or systems that you read about in this section.
2. What needs were these devices invented to meet?
3. Identify any other devices or systems that you know about that can meet these same needs. Why do you think more than one device or system exists to meet the same need?

2.0

An understanding of mechanical advantage and work helps in determining the efficiency of machines.

Key Concepts

In this section, you will learn about the following key concepts:

- mechanical advantage, speed ratios, and force ratios
- mechanical advantage and hydraulics
- measurement of work in joules

Learning Outcomes

When you have completed this section, you will be able to:

- determine the mechanical advantage and the speed ratio of a mechanical device
- modify a model mechanical system to achieve a given mechanical advantage
- identify the reason for differences between theoretical and actual mechanical advantages
- identify work input and output for a simple machine or mechanical system
- describe how hydraulic pressure can create a mechanical advantage

The size of sailboats used to be limited by the size and number of sails that sailors could raise on their own. Once pulley systems were introduced, sailors could lift much larger sails. Larger sails meant bigger boats. Bigger boats were able to carry more people and cargo—and travel farther than ever before. An understanding of simple and complex machines opened up the world for exploration.

By understanding and using simple and complex machines, people have created today's world of machines. In this section, you will learn how a machine can increase a force, and how it affects the speed of an object.

The scientific definition of work is another important concept in understanding machines. Examples in this section will help you develop an understanding of work.

You will also explore more hydraulic machines. You will have an opportunity to build your own simple hydraulic system.

2.1 Machines Make Work Easier

Figure 2.1 A machine can help us do things we wouldn't be able to do on our own.

Imagine that you are on a car trip with friends, far from the nearest city, and suddenly the car gets a flat tire. The driver opens the trunk to take out the spare tire—but there is no car jack! What can you do? The car is too heavy for anyone to lift. The answer is to use a machine—one that you can assemble quickly from available materials. A lever would work. One person can lift a corner of a car using a long lever, such as a sturdy log placed securely on a large rock.

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Winding Mountain Roads

Roads across the open Prairies extend in straight lines for long distances or bend in gentle curves. Roads that have to climb steep hills or mountains bend sharply back and forth. This style of road building is used wherever the slope is too steep for vehicles to drive straight up. Vehicles don't have enough power to climb a steep slope, so each section of road is built so that it raises the vehicle a little higher. After a sharp turn, called a switchback, vehicles can climb higher again. So a mountain road is actually a series of simple machines—ramps that make it easier for vehicles to climb.

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The Newton
The newton (N) is the unit for measuring force. It is named after Sir Isaac Newton, the great scientist who studied force and motion. One newton is equal to the amount of force exerted by Earth's gravity on a mass of about 100 g (e.g., an egg, an orange).

Mechanical Advantage

A machine can make work easier by increasing the amount of force that you exert on an object. In the car example on the previous page, the lever increased the force that the person could exert on the car. A person alone could not exert enough force to lift a car. But using a machine—the lever—made it possible. The scientific explanation is that the lever provided mechanical advantage.

The **mechanical advantage** of a machine is the amount by which a machine can multiply a force. The force applied to the machine is called the **input force.** The force the machine applies to the object is called the **output force**. In the car example in Figure 2.1, the person applies an input force to the long end of the lever. The short end of the lever applies the output force to the car. The output force is much larger than the input force, and the car is lifted. Input and output forces are measured in newtons.

Calculating Mechanical Advantage

You can calculate the mechanical advantage of a machine if you know the input and output forces. The mechanical advantage equals the output force divided by the input force.

$$\text{Mechanical Advantage (MA)} = \frac{\text{Output force}}{\text{Input force}}$$

The mechanical advantage is actually a ratio of forces in the mechanical device. For this reason, mechanical advantage is also called the *force ratio* of the machine.

Here is an example of how to calculate mechanical advantage. This example is shown in Figure 2.2. It takes 45 N to lift a 180-N box with a pulley. (If you lifted it by yourself, you would have to use 180 N.) So the pulley has a mechanical advantage of 4 (180 ÷ 45). This calculation is also shown below. The more a machine multiplies force, the greater its mechanical advantage.

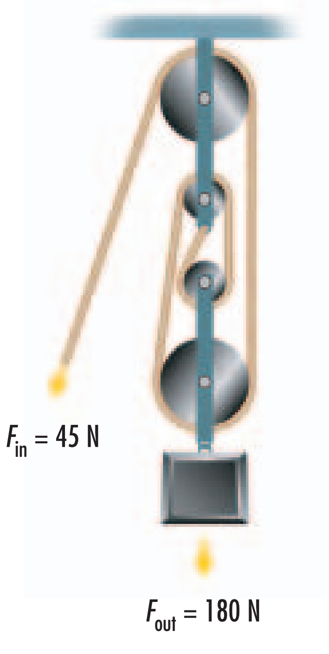

Figure 2.2 This pulley has a mechanical advantage of 4. It multiplies the force you use to pull on it by 4. This enables you to lift a much heavier load than you could on your own, without the pulley.

$$\text{Mechanical Advantage} = \frac{\text{Output force}}{\text{Input force}}$$

or

$$\text{MA} = \frac{F_{\text{output}}}{F_{\text{input}}} = \frac{180\text{ N}}{45\text{ N}} = 4$$

Where F = Force in newtons (N)

SPEED RATIO

Calculating the speed ratio is another way of analyzing how machines work. *Speed* measures the distance an object travels in a given amount of time. A measure of how the speed of the object is affected by a machine is called the **speed ratio**. The speed ratio is calculated by dividing the *input distance* by the *output distance*.

$$\text{Speed Ratio (SR)} = \frac{\text{Input distance}}{\text{Output distance}}$$

Figure 2.3 shows the input distance and output distance for the same pulley that was used in Figure 2.2. The calculation of this pulley's speed ratio is shown below.

$$\text{Speed Ratio} = \frac{\text{Input distance}}{\text{Output distance}}$$

$$SR = \frac{d_{input}}{d_{output}}$$

Where d = distance

$$SR = \frac{4\text{ m}}{1\text{ m}}$$

$$SR = 4$$

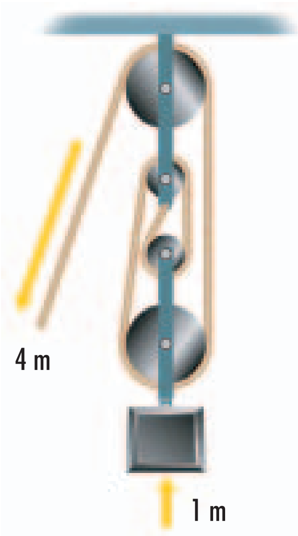

Figure 2.3 This pulley has a speed ratio of 4.

The speed ratio of 4 means that the part of the pulley where you apply the input force moves four times faster than the part where the output force is—the load that you are lifting.

Using these formulas, you can calculate mechanical advantage and speed ratio for any device. Here is an example.

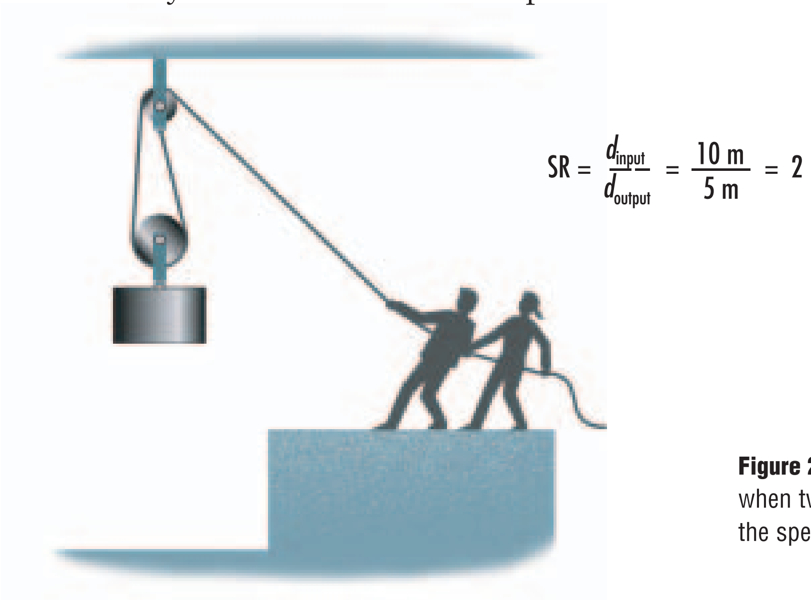

Figure 2.4 A pulley system lifts a load 5 m when two people pull the rope 10 m. What is the speed ratio of the pulley system?

LESS FORCE BUT GREATER DISTANCE

The examples and calculations you've done for speed ratio demonstrate you do not get "something for nothing" when you use a machine. The pulley system in Figures 2.2 and 2.3 multiplies the force you exert, which is an advantage. But in using the pulley, you have to pull much farther than the load actually moves.

You can also see this effect if you use a ramp to help you lift a large object. Figure 2.5 compares two ramps used to raise the same load to the same height. Which ramp has the greater mechanical advantage? Which ramp is longer (which means you have to push the load farther)? What is the speed ratio of the ramp?

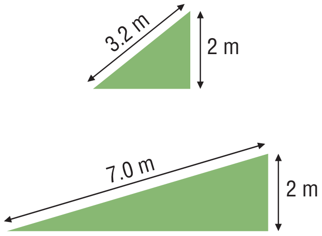

Figure 2.5 What factors affect the mechanical advantage of a ramp? What factors affect the speed ratio?

A MECHANICAL ADVANTAGE LESS THAN 1

So far, we have looked only at examples where the mechanical advantage of a device is greater than 1. In those cases, the machine is multiplying the input force to create a larger output force. But sometimes the mechanical advantage of a mechanical device may be less than 1. Does this mean the machine isn't useful? No, it means that the machine is useful for tasks that don't require a large output force.

Think about the bicycle again. It has a mechanical advantage less than 1. For example, a cyclist may apply an input force of 650 N to the pedals. Through the bicycle's linkages, this results in an output force of 72 N. Recall the formula for calculating mechanical advantage: MA = Output force ÷ Input force = 72 ÷ 650 = 0.1. The mechanical advantage of the bicycle is 0.1.

The output force causes the bicycle to move much faster than the rider would walk. So even though the mechanical advantage is less than 1, the bicycle is still a very useful machine.

Figure 2.6 The mechanical advantage of a bicycle is less than 1. Do you think the speed ratio of a bicycle would be less than or greater than 1?

Problem Solving Activity

Building a Mechanical System

Recognize a Need

Lifting large loads sometimes requires a combination of simple machines. For example, Figure 2.7 shows a boat being hauled out of the water and onto a trailer.

The Problem

Use 2 simple machines to create a mechanical system to raise a 1-kg mass 30 cm with the greatest possible mechanical advantage.

Criteria for Success

For the construction of your mechanical system to be successful, you must meet the following criteria:

- Your mechanical system must consist of at least 2 simple machines.
- It must raise a 1-kg mass at least 30 cm.
- You must use a spring scale to accurately measure the force needed to raise the 1-kg mass with the mechanical system.
- You must achieve the same mechanical advantage with this mechanical system at least twice.

Materials & Equipment

- pulleys
- ramps
- material for levers (lengths of wood)
- string
- plastic gears
- wheel and axle
- screws or adhesives
- spring scale

Figure 2.7 The ramp is an inclined plane that helps to lift the boat onto the trailer. The winch is a wheel and axle with a cable on it. It pulls the boat up the ramp and onto the trailer.

Brainstorm Ideas

TOOLBOX

1 You will be working in teams. As a team, brainstorm possible solutions to the problem. Once you have several solutions, choose the one you think will work the best to meet the criteria listed above.

Build a Mechanical System

2 Create a plan of how you will build your mechanical system. Include a diagram of the mechanical system and a list of materials you will need. Show your plan to your teacher for approval.

3 Assemble your materials and build your mechanical system. Remember that you may need to modify or change your design as you build your mechanical system. Make sure to note any changes you make to your original design.

Test and Evaluate

4 When you have built your mechanical system, test it to see if it meets the criteria. After your test, you may need to make some changes and retest it.

Communicate

5 What was the highest mechanical advantage you were able to achieve?

6 Look at your classmates' mechanical systems. Identify one modification that you could make to your system to improve it.

7 Calculate the speed ratio for your mechanical system. Is it the same as mechanical advantage? If not, why do you think there is a difference?

Comparing Real Mechanical Advantage and Speed Ratio

In Figures 2.2 and 2.3, the calculated mechanical advantage and speed ratio for the pulley system were the same. In real situations, however, they may not be. Here's an example.

A group of students set up the mechanical system shown in Figure 2.8. They measured the length of the ramp and the distance from the desktop to the highest point. With this information, they calculated that the speed ratio for the system should be 2. Having seen the example of the pulley system earlier in this section, they assumed that the mechanical advantage would also be 2.

They then measured the mechanical advantage by using a spring scale to pull the load up the ramp. Using the measured force, they calculated the mechanical advantage. It was less than 2. Why wasn't the mechanical advantage the same as the speed ratio in their experiment?

Figure 2.8 The measured mechanical advantage of this system was less than the speed ratio when the students tested it.

The Effect of Friction

The difference between the theoretical and the real value of the mechanical advantage was the result of friction. Recall from earlier studies that **friction** is a force that opposes motion. Friction is caused by the surface roughness of materials. A rough surface creates more friction than a smooth one. Even surfaces that we think are very smooth are uneven if seen under a magnifying glass or microscope.

Friction can be an important factor in a mechanical system because it opposes motion. This means that extra force is needed to overcome friction whenever you move an object. Think about pushing a box up a ramp. The friction created by the box rubbing against the ramp means you have to push harder than you would if there was no friction. You have to exert a stronger force, so the mechanical advantage of your ramp is less than it would be under ideal conditions, that is, without friction.

The mechanical advantage of a device is affected by friction but the speed ratio is not. Recall that speed ratio is the input distance divided by the output distance. The distance the box is pushed in our ramp example is not changed by friction, so the speed ratio stays the same. The speed ratio represents the *ideal mechanical advantage* of a machine, as if friction did not exist.

Friction also must be considered in a mechanical system because it creates heat. This heat comes from the two surfaces rubbing against each other. If this heat isn't released, it can cause problems in a system. Special fans and lubricants are used to reduce the effect of heat in a system.

Efficiency

Friction affects the mechanical advantage of a mechanical device, so it also affects its efficiency. **Efficiency** is a measurement of how well a machine or device uses energy.

Recall from section 1.0 that early machines used people or animals as energy sources. Later, water, oil, gas, and electricity provided energy for machines. Any machine, such as a pulley lifting an object, loses some energy as it operates. Usually the energy is lost to heat because of friction. We say it is "lost" because it isn't being used directly for the pulley's task of lifting. It becomes heat, which is not needed or wanted for the task.

The more energy that is lost, the less efficient a machine is. Efficiency is calculated as a percentage. So a machine that is 40% efficient loses more energy than one that is 70% efficient. You can calculate the efficiency of a machine by dividing its mechanical advantage by its speed ratio and multiplying the result by 100. For example, a pulley has a speed ratio of 3 and a mechanical advantage of 2.

$$\text{Efficiency} = \frac{\text{Mechanical Advantage}}{\text{Speed Ratio}} \times 100$$

$$\text{Efficiency (\%)} = \frac{\text{MA}}{\text{SR}} \times 100 = \frac{2}{3} \times 100 = 66.67\%$$

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Designing the Best Transmission

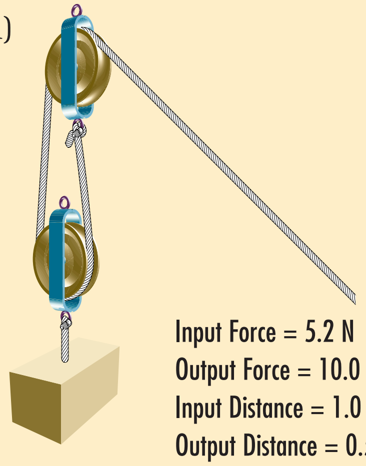
Cars and trucks are designed to handle different sizes of loads and travel in different terrain. Use the Internet or your library to research their different transmissions. How do the mechanical advantage and speed ratio compare for the two different types of vehicles?

In complex machines, the many subsystems are each affected by friction and other factors. Because of this, complex machines are often very inefficient. For example, a typical car engine has an efficiency of only about 15%. That means that 85% of the energy from the gasoline is not used to move the car. Most of it ends up as heat, which is not needed to make the car run. In fact, overheating (too much heat) in a car engine can be a problem.

Check and Reflect

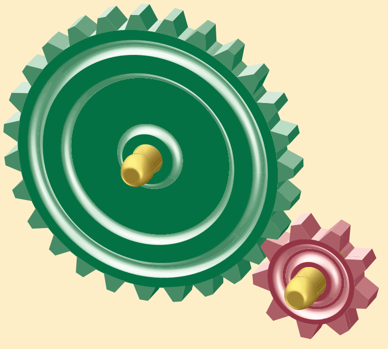
1. Describe how you would measure the mechanical advantage of a bicycle.
2. It takes 350 N of force on the handle of a jack in order to lift a car. It takes 15 000 N of force to lift the car off the ground. Calculate the mechanical advantage of a jack.
3. Calculate the mechanical advantage and the speed ratio for each of the following mechanical devices.

a)



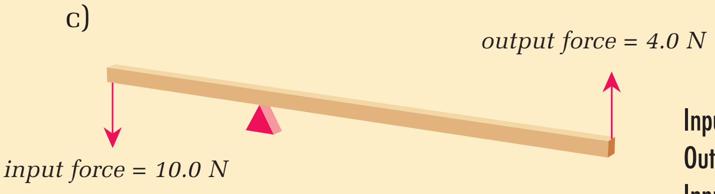
Input Force = 5.2 N
Output Force = 10.0 N
Input Distance = 1.0 m
Output Distance = 0.5 m

b)



Input Force = 7.0 N
Output Force = 20.0 N
Input Distance = 30.0 cm
Output Distance = 10.0 cm

c)



Input Force = 10.0 N
Output Force = 4.0 N
Input Distance = 0.4 m
Output Distance = 0.8 m

4. What is the efficiency of each device in question 3?
5. Why are machines never 100% efficient?

2.2 The Science of Work

You are out with some friends throwing around a Frisbee. You might think it's all play, but you're actually doing work. Later you go home and sit at a table doing homework. You read a page in a science textbook and think about how you will summarize it. You may feel like you are doing work, but according to the scientific definition of work, you aren't.

What does a scientist mean by the word "work"? Look at the photos in Figure 2.9. They all show people and machines doing work, in the scientific sense. Working with a partner, read the captions and try to determine what all these photos have in common. Using that information, develop your own definition of work. Include with your definition a suggestion for how to measure the work done by a person or a machine. Revise your definition as you work through this subsection.

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How Much Work Does It Take?

A 75-kg person does about 406 455 J of work in climbing to the top of the CN Tower in Toronto. A 1-g bee would do about the same amount of work in flying 42 km.

Figure 2.9a) This student has to exert a force on this microscope to lift it up onto the shelf.

Figure 2.9c) This batter is exerting a force to send the ball flying.

Figure 2.9b) This snowplow is exerting a force on this pile of snow to push it out of the way.

THE MEANING OF WORK

The main difference between how we usually think of work and the scientific definition of work is movement. In the scientific sense, **work** is done when a force acts on an object to make the object move. Look again at the photos in Figure 2.9. In Figure 2.9a) the student is exerting a force directly on the microscope to move it. He is doing work on the microscope. In Figure 2.9b), the driver of the snowplow is using the plow to exert a force on the pile of snow to move it. The snowplow is doing work on the pile of snow. In Figure 2.9c), the person is using the bat to exert a force on the baseball. The bat is doing work on the ball.

It's important to remember that movement is needed before you can say that work has been done. In Figure 2.9a), the student lifted the microscope onto the shelf. What if he just stayed in place holding the microscope? The microscope feels heavy because of the force of gravity pulling on it. He probably feels like he's working to prevent it from falling. However, as long as he just stays there without moving, he is not doing work.

In Figure 2.10, these people are trying to push the car out of the sand. They are exerting a strong force on the car. But if the car doesn't move, they aren't doing any work at all, according to the scientific definition of work.

Figure 2.10 These people are trying as hard as they can to push this car out of the sand. But if the car doesn't move, they are not doing work.

Calculating Work

Work can be calculated using the equation $W = F \times d$ where F is the force exerted on an object and d is the distance the object moves because of the force. Force is measured in newtons and distance is measured in metres. The amount of work done depends on two things:

- the amount of force exerted on the object
- the distance the object moved in the direction of the applied force

If you lifted your chair onto your desk, how much work would you do? Assume that you have to exert a force of 50 N to lift the chair and your desk is 0.4 m high.

$W = F \times d$

$W = 50\ \text{N} \times 0.4\ \text{m} = 20\ \text{N·m}$

You did 20 N·m of work. The newton·metre is called a joule, named after the English scientist James Joule. Joule was especially interested in the relationship between work and energy. It's not surprising then that the joule is also the unit used in measuring energy.

Figure 2.11 If you lift the chair or push it along the floor, you are doing work. But if you just hold the chair up without moving, you are not doing any work.

Energy and Work

Energy and work are closely related because without energy, there would be no work. When you ride your bicycle, you exert a force on the pedals. The chain transfers that force to the wheels, causing them to move. Your energy is used to provide the force that drives the pedals that move the wheels of your bike. Work is being done because the force you apply to the pedals causes the bicycle to move.

In a car, the energy to drive the wheels comes from gasoline. An energy source (the gasoline) provides the force that makes the work (the car moving) possible. The machine transfers energy from the energy source to the object, causing the object to move. Earlier you learned that machines help us do work. They help us do work by transferring energy.

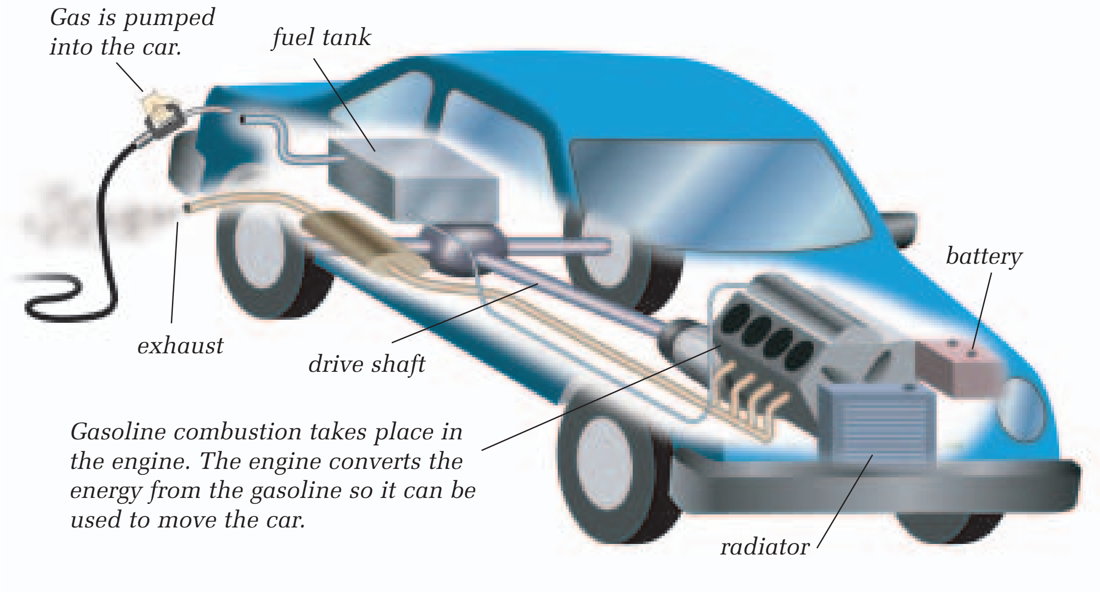

Figure 2.12 Gasoline is the energy source for a car. The combustion of the gasoline causes pistons to move. The pistons are linked to the transmission. Subsystems within the transmission, such as the drive shaft, work together to cause the car's wheels to move. When the car moves, work is done by the whole system. But within the system, work is being done by every part that moves when a force is applied to it.

Work and Machines

In subsection 1.1, you learned about the different kinds of simple machines and how they can help us do work. But using a machine does not mean that less work is done. You use the machine so you don't have to exert as much force. But you still do the same amount of work.

Figure 2.13 The ramp makes it possible for Serena to use less force in helping Kim to the top of the ramp. A much greater force would be needed to lift Kim straight up from the ground to the height of the top of the ramp.

To show why work done with a machine is the same as work done without it, you can calculate work input and work output. The work input is the work needed to use or operate the machine. Look at Figure 2.13. In this example, the work input is the work done by the student using the machine—the inclined plane—to lift the student in the wheelchair. In this case, the pushing student exerts a force of 320 N for a distance of 5 m. You can use the formula for work to calculate the work input:

$$W_{input} = F_{input} \times d_{output}$$

$$\text{Work}_{\text{input}} = 320\ \text{N} \times 5\ \text{m} = 1600\ \text{J}$$

The work output is the work done by the machine. So in the example in Figure 2.13, the machine has lifted the student in the wheelchair up 2 m. The downward force exerted by the student in the wheelchair is 800 N. You can use the formula for work again to calculate the work output.

$$W_{output} = F_{output} \times d_{output}$$

$$\text{Work}_{\text{output}} = 800\ \text{N} \times 2\ \text{m} = 1600\ \text{J}$$

In the example, both the work input and work output equal 1600 J. But the pushing student had to exert a force of only 320 N to move the student in the wheelchair to a height of 2 m. Without the ramp, it would have taken a force of 800 N to lift the student in the wheelchair to a height of 2 m.

Do you think the work input and the work output are always equal?

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Power

Power is the amount of work done in a set period of time. Find out how power is calculated and what units are used for it. In what applications is power measured?

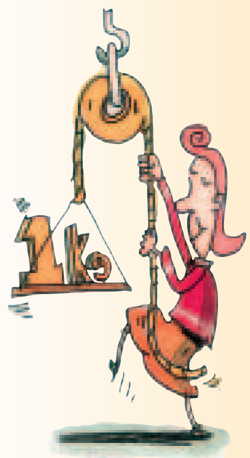
Give it a TRY ACTIVITY

WORK INPUT AND WORK OUTPUT

You can see for yourself if the work input and the work output of a machine are always equal. If you were to lift a 1-kg mass 1 m, you would be doing 9.8 J of work.

How much work would a pulley do lifting a 1-kg mass 1 m? Use a single pulley, a 1-kg mass, a spring scale, and a metre-stick to find out.

Calculate the work input and the work output for the pulley. Are they different? If so, why do you think they are different?



Work and Friction

In subsection 2.1, you learned that the mechanical advantage of a machine does not equal its speed ratio in real situations. The reason is friction. Friction is also the reason that work input does not equal work output in real situations. It affects a machine's efficiency. Earlier you learned one way of calculating efficiency. Efficiency can also be calculated using work input and work output. Here's an example of a device that is 75% efficient.

$$\text{Efficiency} = \frac{\text{Work}_{\text{output}}}{\text{Work}_{\text{input}}} \times 100 = \frac{1200\ \text{J}}{1600\ \text{J}} \times 100 = 0.75 \times 100 = 75\%$$

Check and Reflect

1. Is work being done in the following examples? Explain your answer in each case.
   a) A hiker puts her backpack on.
   b) A gardener pulls on a large weed as hard as he can, but he can't get it out of the ground.
   c) A student memorizes a poem.
2. You use a force of 40 N to push a box of books 3.2 m along the floor. How much work have you done?
3. Use an example to explain the effect of friction on a machine.
4. a) What is work input?
   b) What is work output?
   c) Are they ever equal? Why or why not?
5. At the beginning of this subsection, you developed your own definition of work. How close was your definition to the scientific definition? What changes did you make to your definition as you read through the subsection?
6. Calculate the work done in the following situations:
   a) A 15-N box is lifted 0.5 m.
   b) A 500-N table is pushed 200 cm up a ramp.
   c) A pulley is used to lift a 1000-N piano up 10 m.
7. A person uses a lever to lift a 5-N box 20 cm. Assume that the lever is 100% efficient.
   a) What is the work input done by the person?
   b) What is the work output done by the lever?
8. A person riding a scooter for 1000 m exerts a constant average force of 10 N. Under ideal conditions, what is the work output done by the scooter?
9. A person does 500 J of work to move a box of oranges 25 m. What force was required to move the box?

2.3 The Big Movers—Hydraulics

Figure 2.14 The fluid in the hydraulic system of this backhoe transmits forces that move the levers for lifting heavy loads.

Most machines that move very large objects use a hydraulic system that applies force to levers or gears. A **hydraulic system** uses a liquid under pressure to move loads. A hydraulic system increases the mechanical advantage of the levers in machines such as the backhoe shown in Figure 2.14.

Before hydraulic systems were invented, construction projects were done mainly by hand, using simple machines such as ramps, levers, and the wheel and axle. Large structures made thousands of years ago, such as the Egyptian pyramids, are truly amazing. Imagine moving and placing five-tonne blocks of stone using only ropes, wooden levers, and ramps!

Figure 2.15 In the past, large structures were built with much hard physical work by many people over a long time. Hydraulic systems make it possible for one person to lift huge loads.

Modern construction projects are much safer and can be done much more quickly with the mechanical advantages of hydraulic equipment. Hydraulic systems are used in many places other than construction sites, however. Hydraulic devices perform tasks ranging from raising the height of a hair stylist's chair to controlling the brakes in a car.

Figure 2.16 The hydraulic system enables the hair stylist to raise or lower the chair easily.

Pressure in Fluids

Hydraulic systems work because they use fluids under pressure. From earlier studies, you may recall that **pressure** is a measure of the amount of force applied to a given area. It can be written as an equation: $p = F/A$, where p is pressure, F is force, and A is area. The unit of measurement for pressure is the pascal (Pa). This unit is named after Blaise Pascal, a scientist who did important research on pressure in fluids. One pascal equals the force of 1 newton over an area of 1 m^2. This is such a small amount of pressure that scientists usually use kilopascals when recording pressure measurements. Note that pressure can also be measured in newtons per square centimetre (N/cm^2).

In his research, Pascal discovered that pressure applied to an enclosed fluid is transmitted equally in all directions throughout the fluid. This effect is known as **Pascal's law**. This law makes hydraulic and pneumatic systems possible. These two types of systems both use fluids under pressure to move loads. Hydraulic systems use liquids, and pneumatic systems use gases (usually air). You can find out more about pneumatic systems in Unit A: Mix and Flow of Matter.

A common application of Pascal's law is the hydraulic jack. A jack is any device used to lift something. You may have seen a hydraulic jack used for lifting or moving objects in a store. Figure 2.17 shows how a simple hydraulic jack works.

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Air Pressure

You have probably heard of low or high pressure systems in weather. We don't think of air having weight. But it's the weight of the air above us that creates pressure. Average air pressure at sea level is about 100 kPa or 100 000 N of force for every square metre.

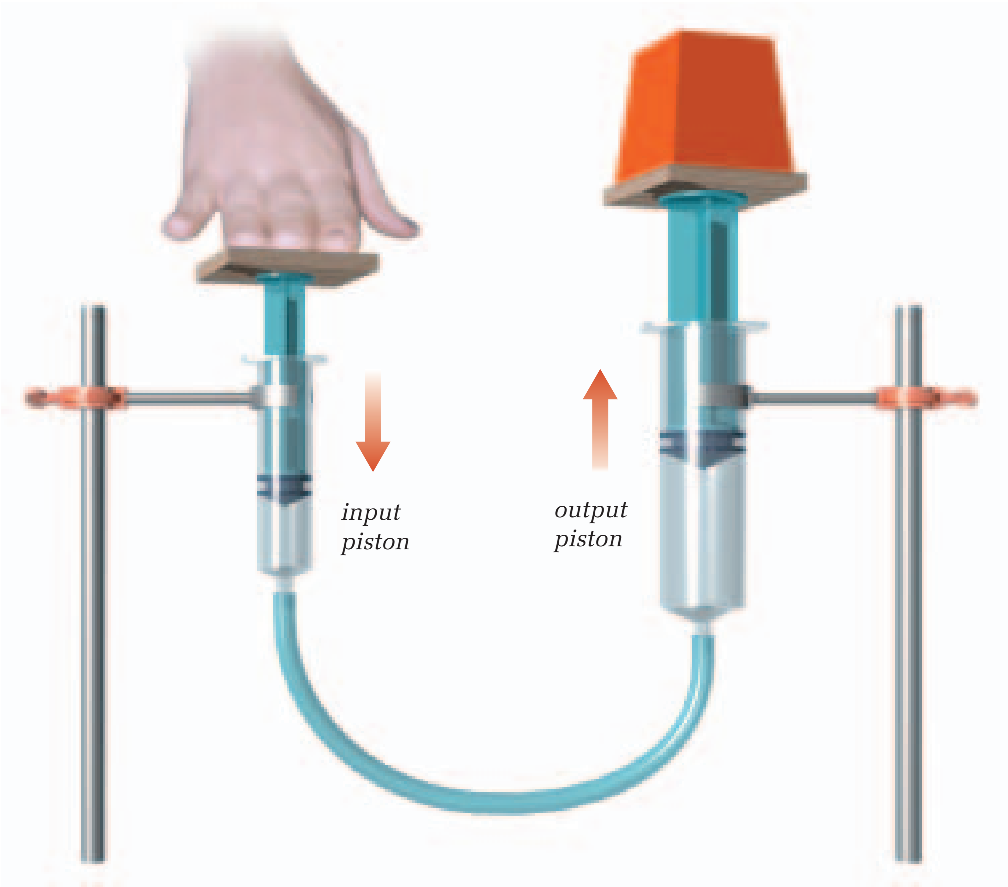

Figure 2.17 A simple hydraulic jack works because of Pascal's law.

A Piston Creates Pressure

In hydraulic systems, the pressure is created using a piston. A piston is a disk that fits tightly inside a cylinder. As the disk moves inside the cylinder, it either pushes fluid out or draws fluid into the cylinder. Pistons can be very small (e.g., 1 cm^2 in a small syringe). Or they can be very large (e.g., a few square metres in a hydraulic car hoist).

Hydraulic devices use a combination of two pistons attached to either end of a cylinder or flexible pipe. Figure 2.17 shows the parts of a hydraulic system. The first piston is the *input piston*. This piston is used to apply the force to the fluid, which creates pressure in the fluid. The fluid transfers this pressure to the *output piston.* The fluid transfers the pressure equally in all directions. So the pressure on the output piston is equal to the pressure created by the input piston.

This pressure exerts a force on the output piston, which causes the piston to move. The pressure in the fluid provides the mechanical advantage that makes hydraulic systems so useful. Let's look at how it does that.

math Link

The human heart is an excellent pump. It distributes blood throughout the body, creating pressure in the blood vessels. Normal maximum blood pressure for a healthy person is 16 000 Pa. The artery carrying the blood from the heart has an average diameter of 1.5 cm. Calculate the force supplied by the heart to produce normal blood pressure.

Inquiry
Activity

Mechanical Advantage in a Hydraulic Jack

Before You Start ...

A jack is any device used to lift objects. You will use syringes and flexible tubing to create a model of a hydraulic jack. The plungers in the syringes are pistons.

Materials & Equipment

- 2 50-mL syringes, each with a platform
- 10-mL syringe with platform
- small plastic tub
- water
- 30 cm of latex tubing
- 4 burette clamps
- 2 support stands
- 1-kg mass

The Question

How does pressure create mechanical advantage in a hydraulic jack?

The Hypothesis

Write a hypothesis that describes how the pressure in a hydraulic jack creates a mechanical advantage. Hint: Think about the relationship between force and piston area in a hydraulic system.

Procedure

1. Measure the diameter of the plungers in one of the 50-mL syringes and in the 10-mL syringe. Calculate the area of each plunger and enter it in your table.
2. Connect the two 50-mL syringes with the latex tubing. Remove the plungers from both syringes. As shown in Figure 2.18, hold the syringes at the same level. Have your partner pour water into one until both are full.
3. Remove all the air from both syringes and the tubing. Insert the plunger into one syringe and push it all the way down. Use the plastic tub to catch the overflow from the other syringe. Insert the plunger into the second syringe and push it halfway down. No air should be left in the syringes or the tubing.

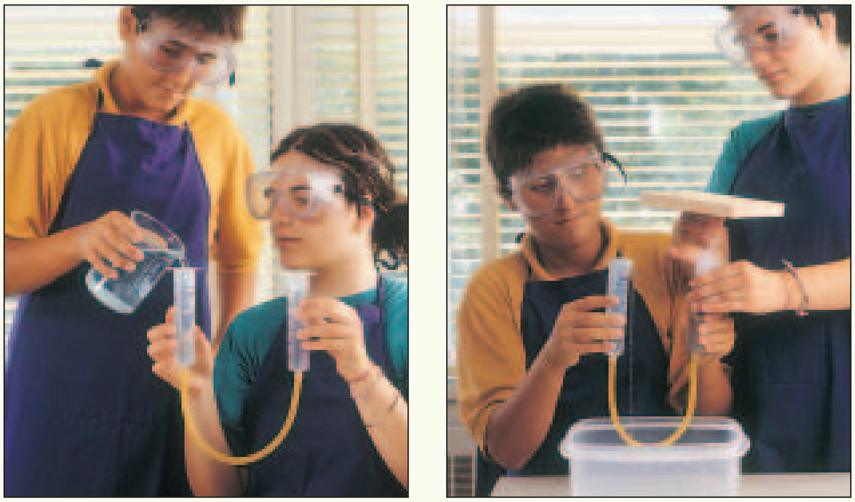

Figure 2.18 Steps 2 and 3. It is important to make sure that there is no air in the syringes before you begin.

4. Check that the plungers move easily in each syringe. If one or both of them stick, move first one plunger, then the other until they slide easily.
5. Using the burette clamps, mount each syringe on a support stand. Have your partner hold one support stand steady and place the 1-kg mass on that syringe's platform. Hold the other support stand steady as you push down on that syringe's platform until the mass on the other syringe moves.

6. Move the 1-kg mass over to the other platform. Hold both support stands steady as you push down on the empty platform until the mass moves. Be aware of how much force you needed to move the mass in this set-up. Record this amount of force as your "control force."
7. Remove the 1-kg mass and take both syringes off the support stands. Carefully remove the latex tubing from one of the 50-mL syringes, allowing the water to drain out of both syringes and the tubing into the plastic tub. Keep the latex tubing attached to the other 50-mL syringe.
8. Connect the 10-mL syringe to the 50-mL syringe with the latex tubing. Fill the syringes with water, as described in step 2. But this time, insert the plunger in the 50-mL syringe and push it down only halfway. Then insert the plunger in the 10-mL syringe. As before, check that the plungers move easily.
9. Repeat steps 4 and 5. Be aware of how much force you needed to move the mass each time in this set-up. Enter this information as "more than control force" or "less than control force" in your table.

Collecting Data

10 Record your observations in a table like the one shown below.

Area of the plunger		Force needed
Plunger pushed on	**Plunger supporting 1-kg mass**	
plunger in 50-mL syringe	plunger in 50-mL syringe	control
plunger in 50-mL syringe	plunger in 10-mL syringe	
plunger in 10-mL syringe	plunger in 50-mL syringe	

Analyzing and Interpreting

11 Why was the word "control" used to identify the force you used to push down the mass when both syringes were the same size?

12 Which situation allowed you to use the least amount of force to raise the 1-kg mass?

13 a) A 1-kg mass exerts a force of 10 N. Use the formula $p = F/A$ to calculate the pressure exerted on the water by each plunger when the 1-kg mass was sitting on it.

b) Which plunger exerted more pressure on the water?

c) Which plunger exerted more pressure on the opposite plunger? Explain your answer.

Forming Conclusions

14 Use your observations and diagrams to prepare a brief summary report explaining how pressure creates mechanical advantage in a hydraulic system. Hint: Recall that mechanical advantage is a ratio of output force to input force.

MECHANICAL ADVANTAGE IN HYDRAULIC SYSTEMS

The mechanical advantage in a hydraulic system comes from the fluid pressure in the system. Figure 2.19 shows another example of a simple hydraulic jack. The force applied to the input piston creates pressure in the fluid. This pressure is transferred throughout the fluid and presses on the output piston. This creates a force on the output piston. So when you push on the smaller input piston, it presses on the fluid, which presses up on the larger output piston, which lifts the object.

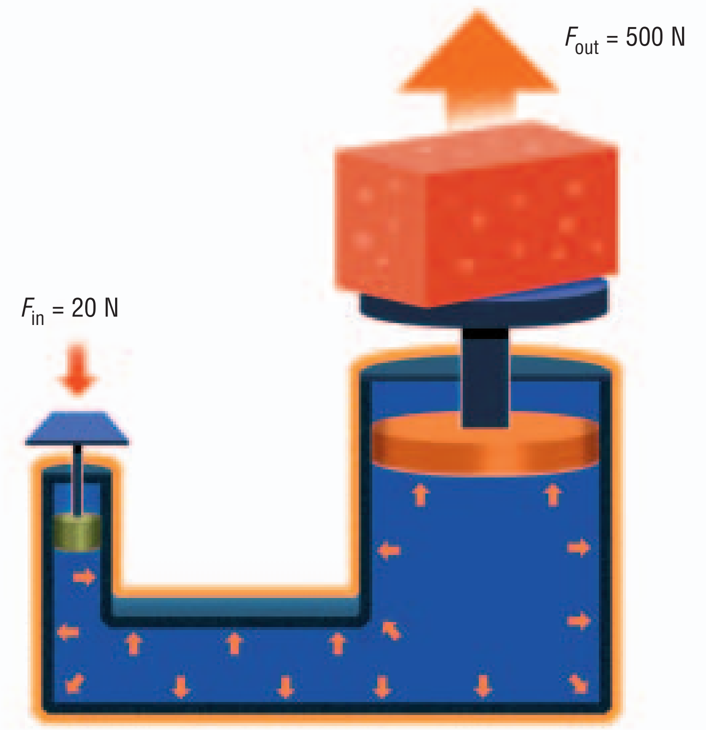

Figure 2.19 This hydraulic jack has a mechanical advantage of 25.

You can calculate the mechanical advantage of a hydraulic jack if you know the input and output forces. In the example shown in Figure 2.19, the input force is 20 N and the output force is 500 N. Recall that the formula for calculating mechanical advantage is MA = Output force ÷ Input force. So for this jack:

MA = 500 N ÷ 20 N = 25

The jack's mechanical advantage is 25.

Earlier in this unit, you calculated the mechanical advantage for pulleys and other mechanical devices. Recall that these mechanical advantages were numbers like 4, 8, or 12. So 25 is a large mechanical advantage.

PRESSURE AND MECHANICAL ADVANTAGE

The reason for the large mechanical advantage in a hydraulic system is the ability of the fluid to transmit pressure equally. It allows you to use a smaller force on the small piston to produce a larger force on the large piston.

Recall that $p = F/A$. Assume the small piston has an area of 4 cm^2 and the force it applies to the fluid is 20 N.

$$p = F/A = 20\ N/4\ cm^2 = 5\ N/cm^2$$

So the small piston creates a pressure of 5 N/cm^2 in the hydraulic fluid.

From Pascal's law, we know that the pressure the small piston creates is the same everywhere in the fluid. So this is pressure at the large piston. The large piston has an area of 100 cm^2. What force is exerted on the large piston? This force will push the piston up, which will raise the 500-N load in our example.

Think of the force and area at each piston as ratios that have to be equal. They both have to equal the pressure of 5 N/cm^2 in our example. So the force of the small piston divided by the area of the small piston must equal the force of the large piston divided by the area of the small piston. Here's how that looks:

$$\frac{\text{Force of the small piston}}{\text{Area of the small piston}} = \frac{\text{Force of the large piston}}{\text{Area of the large piston}} = 5\ N/cm^2$$

Our ratios are: $\frac{F_{small}}{A_{small}} = \frac{F_{large}}{A_{large}}$

$$\frac{20\ N}{4\ cm^2} = \frac{X}{100\ cm^2}$$

We solve the equation and find that X equals 500 N. So the force exerted on the large piston by the fluid is 500 N—much larger than the 20-N force that the small piston exerted on the fluid in the first place.

This example shows the difference in forces created within a hydraulic system. This difference provides the mechanical advantage in a hydraulic system. Their large mechanical advantages make hydraulic systems useful in many applications—from amusement park rides to pipelines.

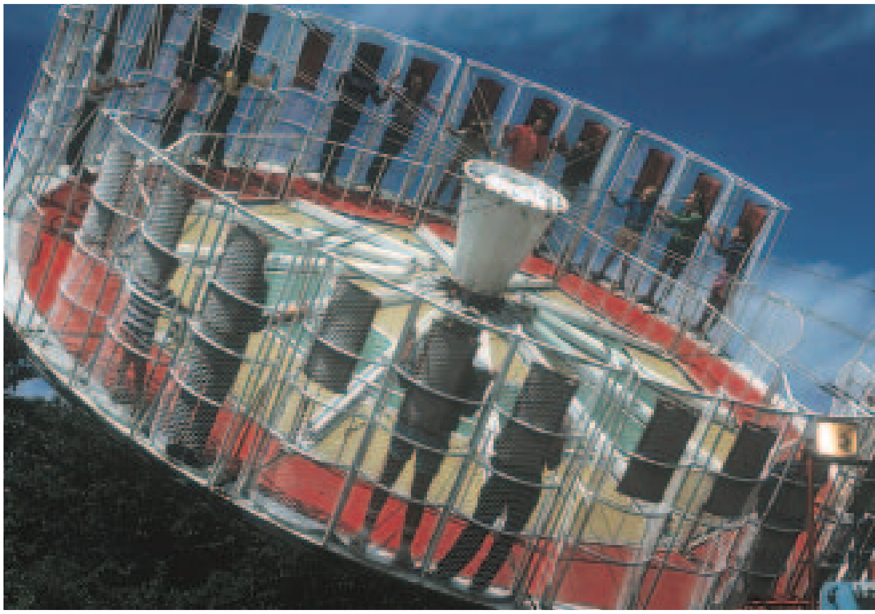

Figure 2.20 This ride uses a hydraulic system to create thrills. Hydraulics in the base of the ride lift and slant the platform as it spins.

Larger Force—Greater Distance to Move

You may recall from earlier in this unit that the mechanical advantage of simple machines came at a cost. For example, the mechanical advantage of a lever produced a larger output force. The shortcoming of the lever is that the input force has to move a greater distance than the output force. The mechanical advantage of hydraulic systems has a similar shortcoming. To increase the force on the output piston, the input piston has to move a greater distance.

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Hydraulic and Pneumatic Devices

Use the Internet or your library to determine whether each device below is hydraulic or pneumatic. Where possible, try to determine the mechanical advantage of each device.

- bicycle pump
- front-end loader
- flap controls on an airplane
- air conditioner

Check and Reflect

1. What is a pascal? What does it measure?
2. How do the sizes of the pistons affect the pressure in a hydraulic system?
3. Describe how forces are transferred in a fluid.
4. A hydraulic lift has 2000 N applied to an input piston that has an area of 50 cm^2. The output piston has an area of 200 cm^2.
   a) What is the pressure on the liquid exerted by the input piston?
   b) Will the force on the output piston be the same or less than the force exerted by the input piston? Explain your answer.