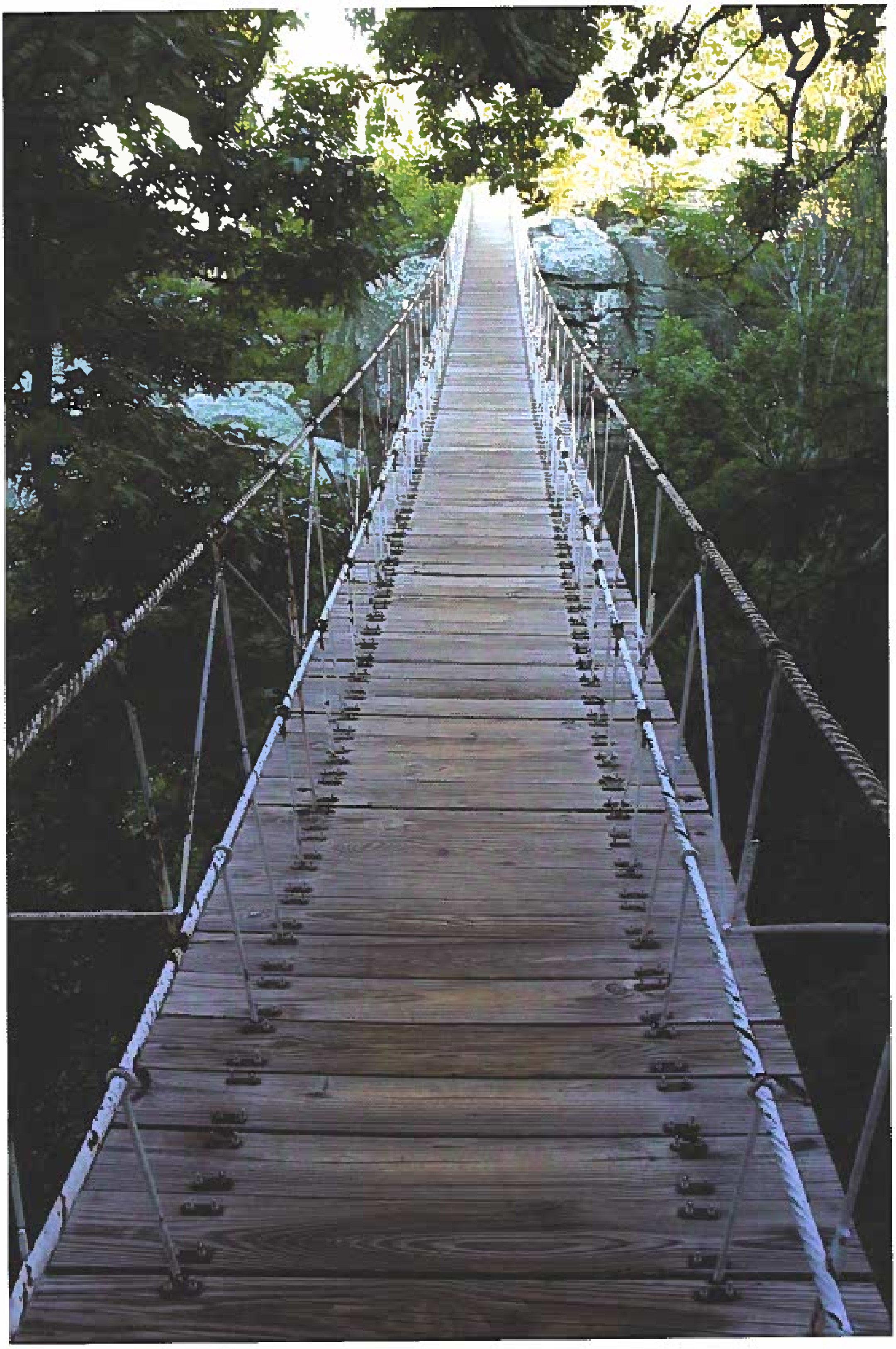


Not all bridges are large structures. Smaller bridges, such as this footbridge, must also be designed for strength and safety. What materials did the designers use in this bridge? How is the bridge supported? Where would a bridge like this be appropriate?

CHAPTER 8

Machines

Better by Design

Charles Harrison designs machines used around the home

In this walk-behind lawn mower, the gas tank is placed with the engine for a more unified appearance.

Charles "Chuck" Harrison is one the most productive and respected American industrial designers of his time. He has been involved in the design of more than 750 consumer products that have improved the life of millions. Harrison helped design the portable hair dryer, toasters, stereos, lawn mowers, sewing machines, and the see-through measuring cup. He worked on power tools, fondue pots, and stoves. Among his most important designs was the first plastic garbage can. The tough plastic can was lighter and more durable than the traditional metal can. The round container evolved shortly into the familiar square green hulk with two wheels and raccoon-proof lid.

Harrison designed this hedge trimmer with plastic parts to minimize its weight.

"My best efforts resulted in products that did their job as expected—you look at it, right away guess what it is supposed to do, and that's exactly what it does."

Reading Target

Finding the Meaning of Unknown Words

Before you read this chapter, skim through it briefly and identify any words you do not know. Record these words using the Reading Target graphic organizer at the end of the chapter. Then read the chapter carefully. Use the context of the sentence to try to determine what each word means. Record your guesses in the graphic organizer also. After you read the chapter, follow the instructions with the graphic organizer to confirm your guesses.

Key Terms

friction
gear
hydraulics
inclined plane
lever
linkage
lubrication
machine
mechanical advantage
mechanism
moment
pneumatics
power
pressure
pulley
screw
torque
velocity
viscosity
wedge
wheel and axle
work

Objectives

After reading this chapter, you will be able to:

- Identify the six simple machines.
- Describe types of gears and list uses for each type.
- Explain methods of applying pressure to increase or decrease effort applied to an object.
- Design and make a product that incorporates one or more mechanisms.
- Explain how friction can be reduced or overcome in a system.

Useful Web sites:
www.alifesdesign.com/about.asp
www.nationaldesignawards.org/2008/honoree/charles-harrison/?p=109

Machines help us to produce food on the land and make the electronics you play with. They help us dig trenches and bore tunnels. Around the home, the automatic washing machine, lawn mower, and vacuum cleaner lighten our workload. The dentist's drill removes decay from our teeth. The jet plane speeds us to our vacation site.

A *machine* is a device that uses energy to do some kind of work. For example, a lawn mower uses gasoline to trim the lawn. Machines do not need to be large or complicated. A knife, a bottle opener, and a claw hammer are also machines.

Machines have been used for thousands of years to make work easier. For example, people discovered that they could lift heavy objects more easily by throwing a rope over a tree branch. This allowed them to pull down instead of lifting to move the objects. This idea was later refined to use a wheel with a groove for a rope, chain, or belt. See Figure 8-1.

Simple Machines

Over the years, six basic types of machines were developed. They include the lever, pulley, wheel and axle, inclined plane, wedge, and screw. We refer to these as *simple machines*. These six simple machines can be divided into two groups. One is based on the lever, and the other is based on the inclined plane. See Figure 8-2.

Figure 8-1. Changing the direction of applied force makes it easier to lift heavy objects. As the woman pulls down on the rope, the pail moves upward.

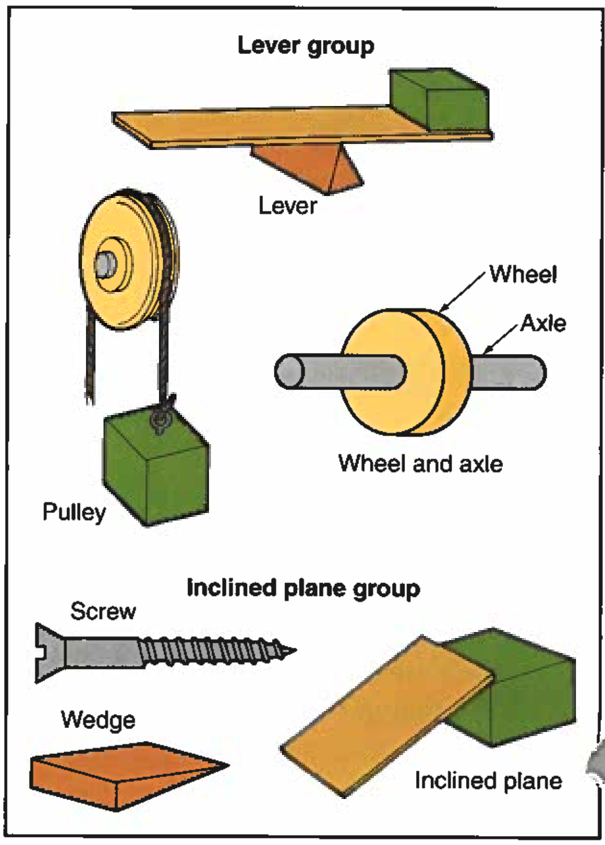


Figure 8-2. The six simple machines continue to be important inventions.

The Lever

You have probably played or seen a game of baseball. See **Figure 8-3**. A baseball bat is a lever. A *lever* has a fulcrum, effort, and resistance. The fulcrum is the point where the bat is held. The batter's muscles supply the effort, and the resistance is the ball. See **Figure 8-4**.

To understand the principle of the lever, look at the boy in **Figure 8-5**. He is using a branch to move a heavy rock. The branch is the lever. The mass of the larger rock is the resistance (R). The boy's muscle power pushing down on the lever provides the effort (E). The smaller rock on which the lever is pivoting is the fulcrum (F). These three elements—resistance, effort, and fulcrum—are always present in a lever. However, they can be arranged in different ways to create three different classes of levers.

In a Class 1 lever, the fulcrum is placed between the effort and the resistance, as shown in **Figure 8-6**. Some applications of Class 1 levers are illustrated in **Figure 8-7**.

In Class 2 levers, the resistance is placed between the effort and the fulcrum, as shown in **Figure 8-8**. Some applications of Class 2 levers are illustrated in **Figure 8-9**.

Figure 8-3. Baseball players use a bat as a lever to strike the baseball with greater speed.

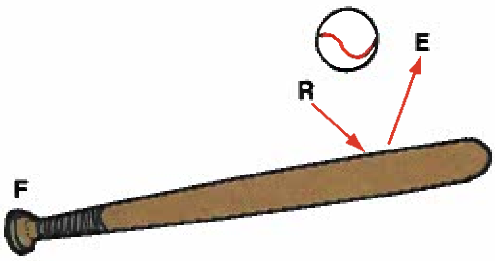


Figure 8-4. The baseball bat is an example of a lever: F–Fulcrum; R–Resistance; E–Effort.

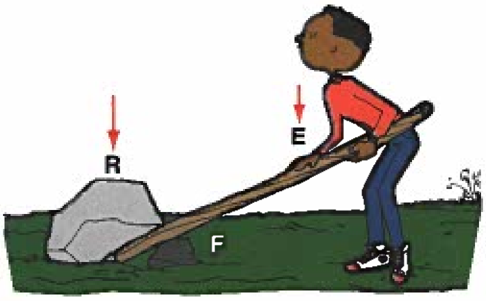


Figure 8-5. A lever being used to move a heavy load.

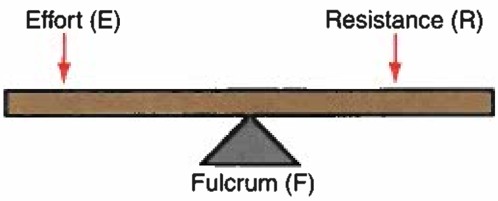


Figure 8-6. In a Class 1 lever, the fulcrum is between the effort and resistance.

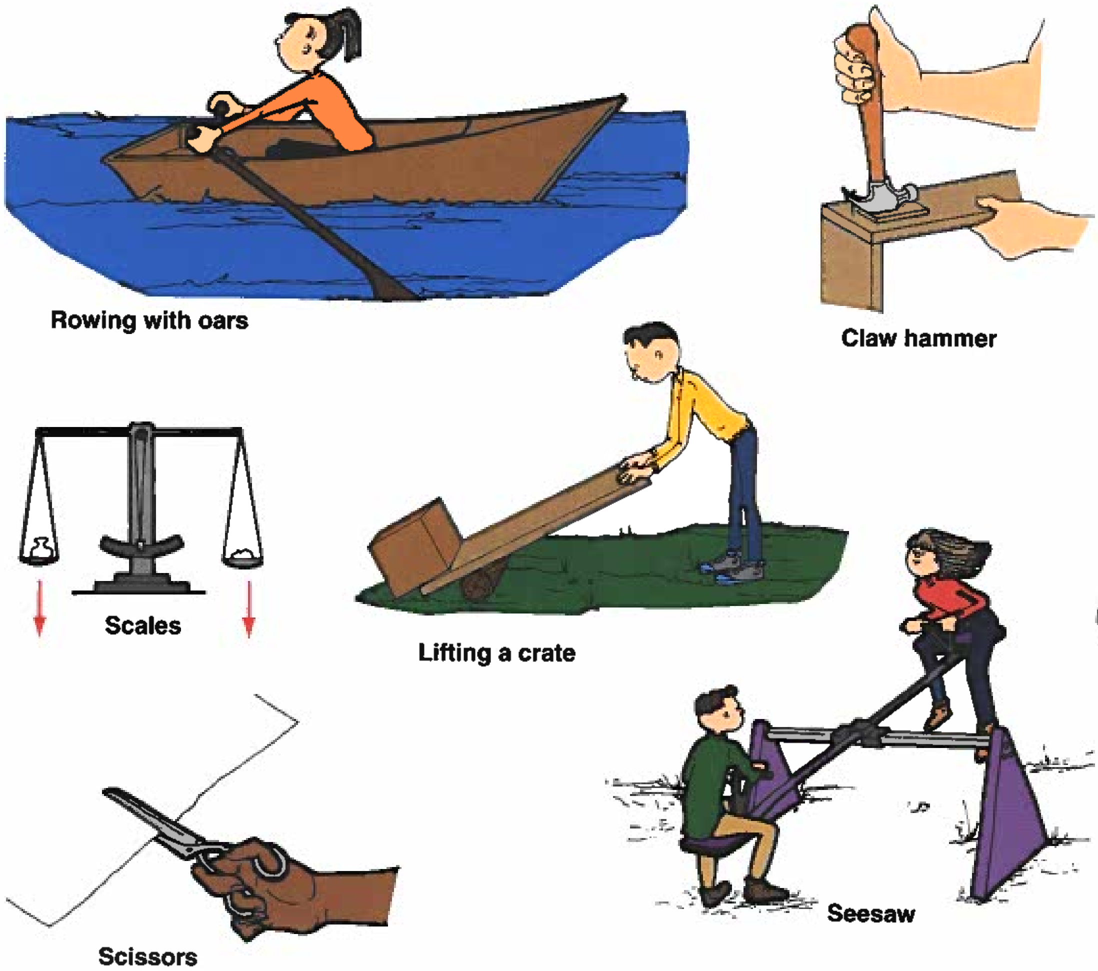


Figure 8-7. Everyday uses of Class 1 levers.

In Class 3 levers, the effort is applied between the resistance and the fulcrum, as shown in **Figure 8-10**. Some applications of Class 3 levers are illustrated in **Figure 8-11**.

From the many examples shown, you can see that some levers are designed to increase the force available. Examples are a wheelbarrow, a bar used to move a crate, and a garden spade. Other levers are designed to increase the distance a force moves or the speed at which it moves. Examples are a fishing rod and a human arm.

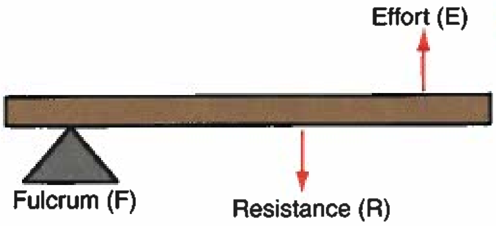


Figure 8-8. In a Class 2 lever, the resistance is between the effort and fulcrum.

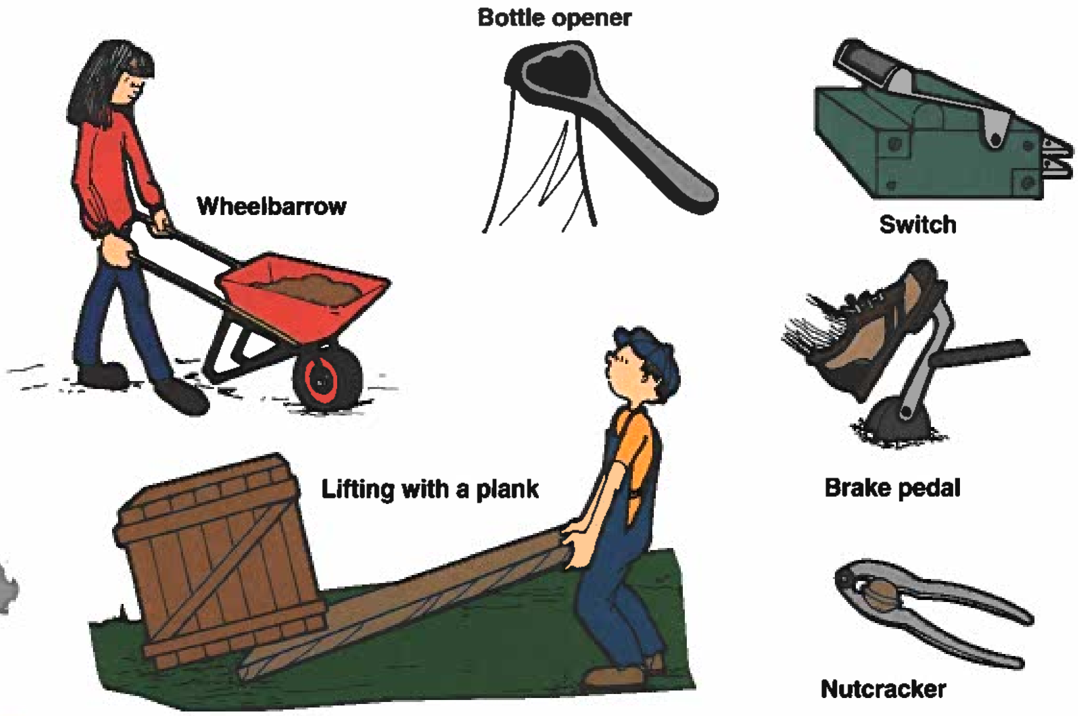


Figure 8-9. Everyday uses of Class 2 levers.

Mechanical Advantage

Using a smaller effort to move a large resistance creates an advantage. This is called the ***mechanical advantage*** of the lever.

Mechanical advantage is equal to the resistance divided by the effort. The greater the resistance that can be moved for a given effort, the greater the mechanical advantage is. The formula is:

$$\text{Mechanical Advantage (M.A.)} = \frac{\text{Resistance}}{\text{Effort}}$$

For example, if a lever can make it possible to overcome a resistance of 90 newtons (N) when an effort of 30 N is applied, the mechanical advantage is 3. The newton (N) is the metric unit of force or effort.

$$\text{(M.A.)} = \frac{90\text{N}}{30\text{N}} = 3$$

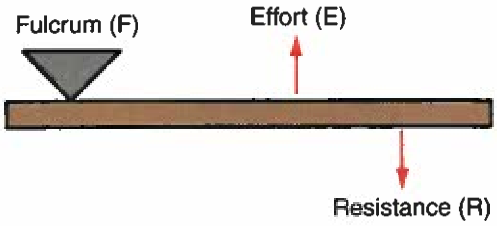


Figure 8-10. In a Class 3 lever, the effort is between the resistance and fulcrum.

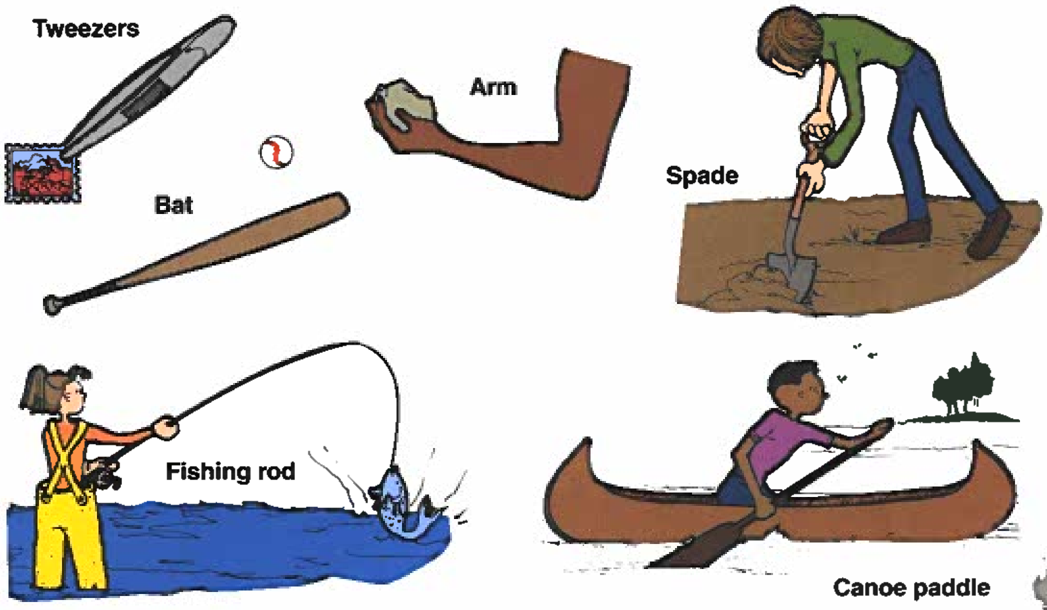


Figure 8-11. Everyday uses of Class 3 levers.

In other words, the human effort applied is being multiplied by the machine. In this case, the machine is a lever. The effort required becomes less as the fulcrum and resistance are brought closer together. However, as the fulcrum and resistance are moved closer, the load moves a shorter distance. See **Figure 8-12**.

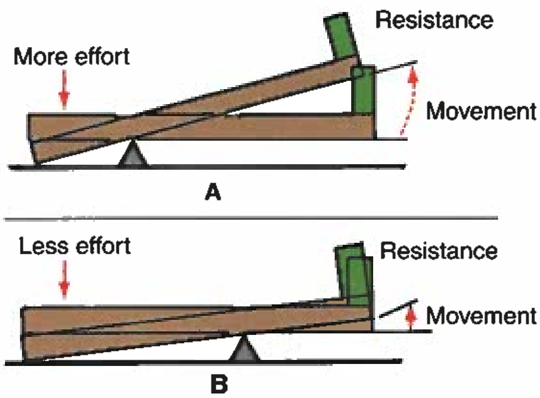


Figure 8-12. Moving the fulcrum of a Class 1 lever affects both the effort required and the distance the object is moved.

Science Application

Sports and Levers

Without realizing it, people use the principle of leverage in many sports, including tennis, baseball, and golf. For example, when a tennis player serves a ball, the player's arm and tennis racket work together as a lever.

A pitcher on the mound winds up, draws the right side of his body back and his left foot forward. Suddenly, he throws his weight forward, flings his arm forward, and lets fly with a fast ball. His arm has been used as a lever.

A golfer tries to keep his golf club on the correct swing path. As his arm and club come back down, he reaches a point where the elbow and right hip are close together. This position creates a lot of leverage.

Science Activity

Look at the three diagrams labeled A, B, and C. In each diagram, state where the *resistance*, *force*, and *fulcrum* are found. Also state whether the player's movement is an example of a first, second, or third class lever.

A

B

C

Moments and Levers

Imagine a lever with a fulcrum in the middle. On one side is an effort and on the other a resistance. When at rest, this lever is said to be balanced. If the effort is increased, the lever turns in a counterclockwise direction. If the resistance is increased, the lever turns in a clockwise direction, as shown in **Figure 8-13**. The turning force is called a *moment*.

The moment depends on two things: the effort and the distance of the effort from the fulcrum.

$$\text{Moment} = \text{Effort} \times \text{Distance}$$

If a beam is in balance, the clockwise moments are equal to the counterclockwise moments.

$$4 \times 50 = 8 \times 25$$

The levers discussed so far have been used to increase force, distance moved, or speed. Levers can also be used to reverse the direction of motion.

Think of a lever with a fulcrum in the center. If it pivots about its fulcrum, the ends move in opposite directions. One end moves down, and the other end moves up. See **Figure 8-14**. A single lever with a pivot in the center reverses an input motion.

This idea is used in linkages. A *linkage* is a system of levers used to transmit motion. **Figure 8-15** illustrates a reverse motion linkage. The input force and output force are equal.

If the pivot is not at the center, the input force is increased or decreased at the output. This is shown in **Figure 8-16**.

The Pulley

The *pulley* is a special kind of Class 1 lever. See **Figure 8-17**. Its action is continuous. The resistance arm is the same length as the effort arm. The length of each arm is the radius of the pulley. See **Figure 8-18**.

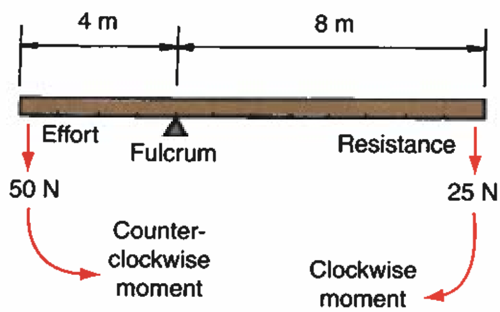


Figure 8-13. Forces acting on a lever are called *moments.*

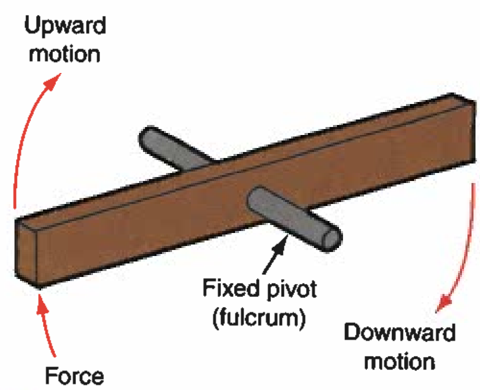


Figure 8-14. Some levers are designed to change motion.

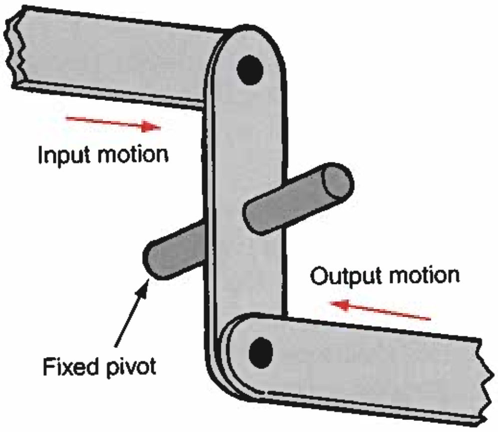


Figure 8-15. In a reverse motion linkage, the pivot is fixed at the center of one lever. Input force equals output force.

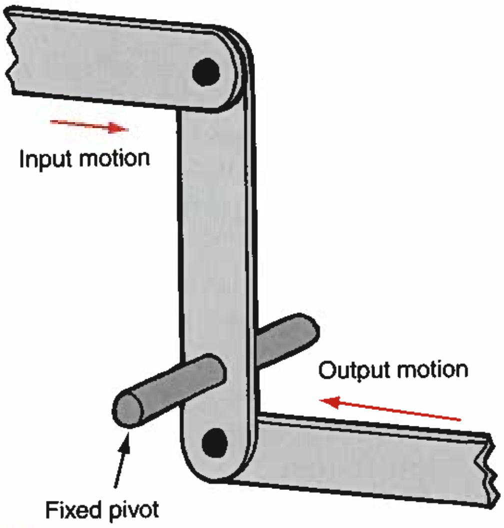


Figure 8-16. In this example, the pivot has been moved closer to the output motion. Is the input force increased or decreased at the output?

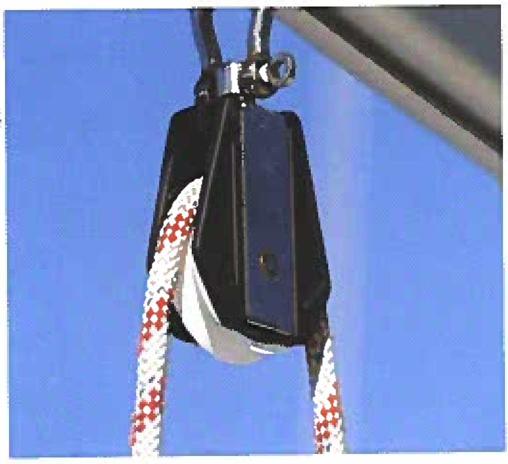


Figure 8-17. A simple pulley changes direction once.

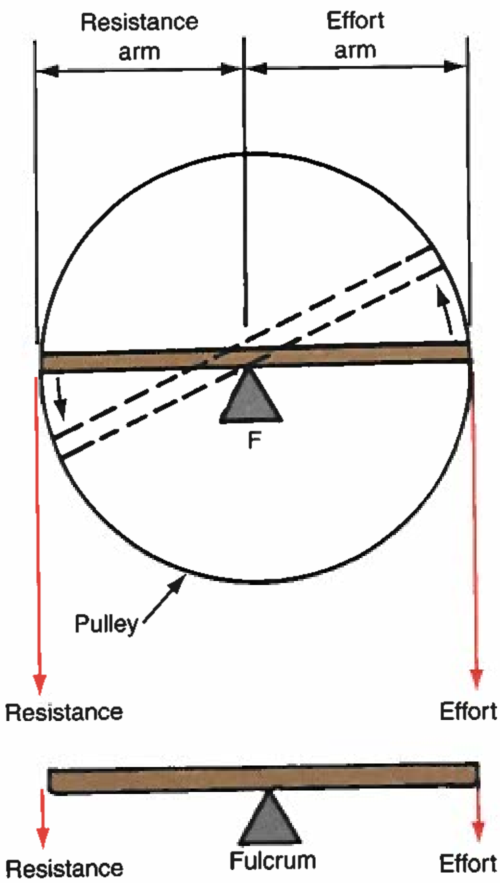


Figure 8-18. Look at this drawing and explain why a pulley is a special type of Class 1 lever.

Pulleys are used to lift heavy objects. See Figure 8-19. A bale of hay can be lifted into a hayloft using a single pulley suspended from a beam. A car engine hoist enables one person to lift a car engine having a mass of over 450 lb. (200 kg). Cranes use pulleys to lift enormous loads.

Two types of pulleys are used to lift heavy objects: fixed and movable. In a single, fixed pulley system, Figure 8-20, the effort is equal to the resistance. There is no mechanical advantage. It is easier, however, for the operator to pull down instead of up. There has been a change in direction of force. The distance moved by the effort (effort distance) is equal to the distance moved by the resistance (resistance distance).

A single, movable pulley system has a mechanical advantage of two. Both ropes support the resistance equally. See Figure 8-21. The amount of effort required is half of the resistance. The disadvantage is that the operator must pull upward. Also, the effort distance is two times the resistance distance. In all pulley systems, as the effort decreases, the effort distance increases.

To have the advantages of change of direction and decreased effort, movable and fixed pulleys can be combined as shown in Figure 8-22. In both examples, the mechanical advantage is two. However, the effort must be exerted over twice the distance.

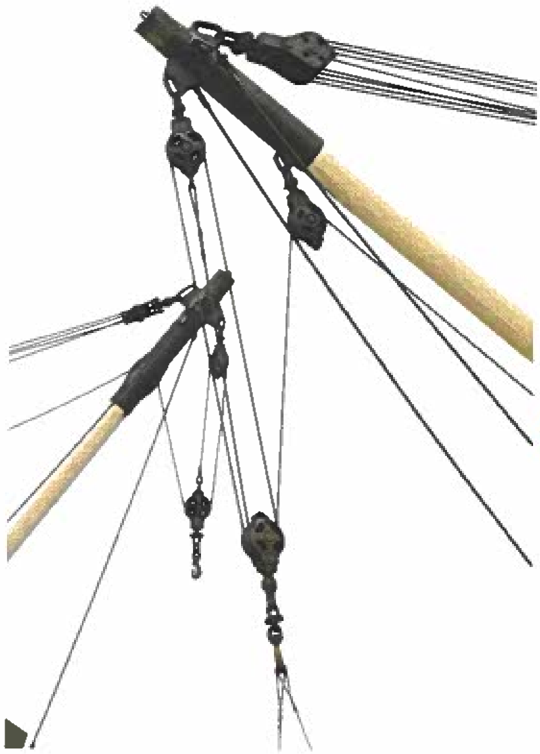


Figure 8-19. Pulleys can be used alone or together in different ways to lift and move large objects easily.

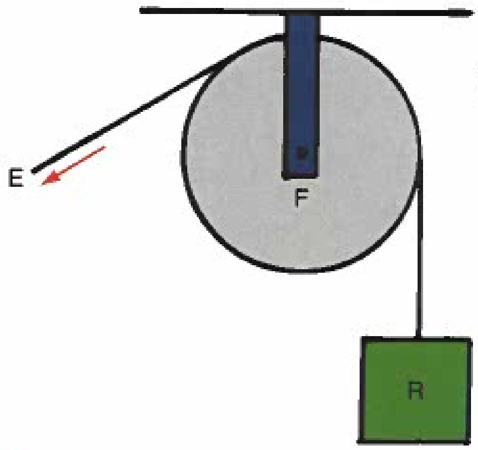


Figure 8-20. With a single, fixed pulley, the effort is equal to the resistance. There is no mechanical advantage.

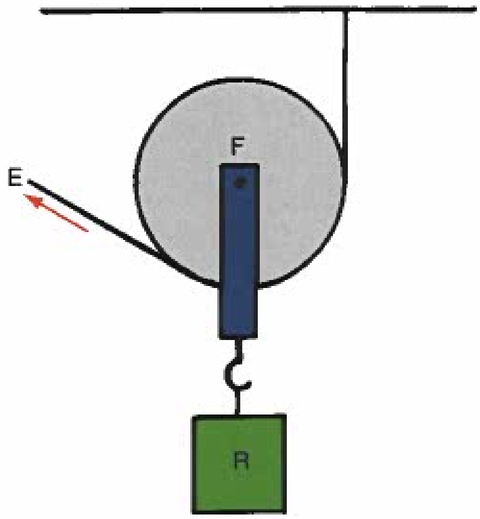


Figure 8-21. With a single, movable pulley, effort equals half the resistance. The effort moves twice the distance of the resistance.

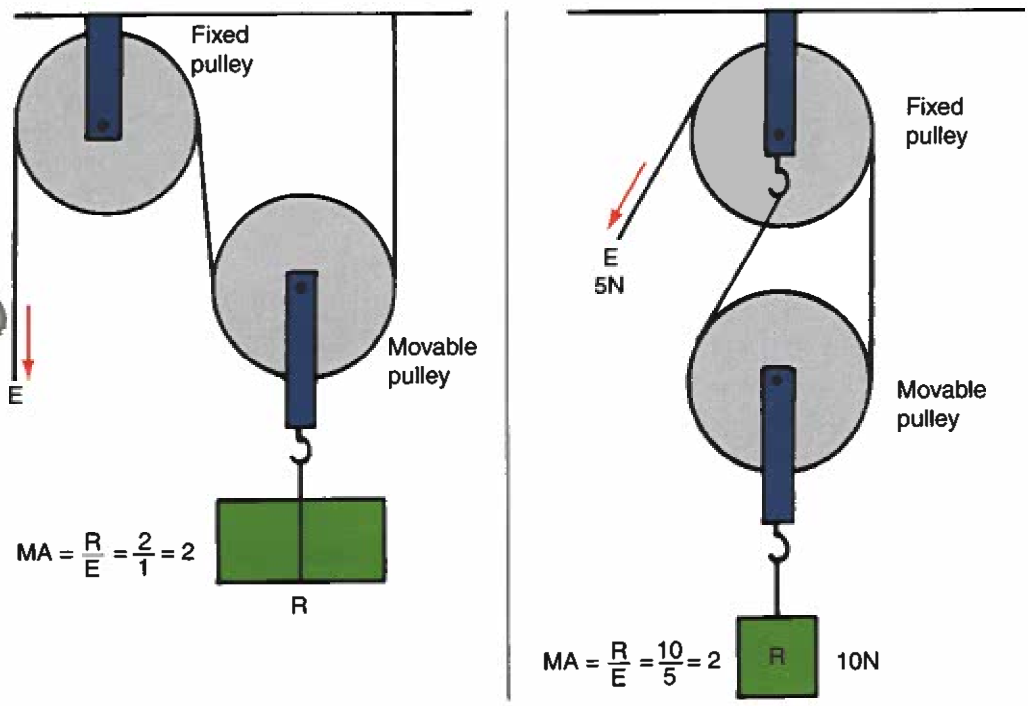


Figure 8-22. The fixed pulley changes direction of the effort. The movable pulley decreases the amount of effort required.

Pulleys may also be used to transmit motion, increase or decrease speed, reverse the direction of motion, or change motion through 90°. See Figure 8-23. These types of pulley systems may be used in cars (fan belt), upright vacuum cleaners, washing machines, and electrical appliances.

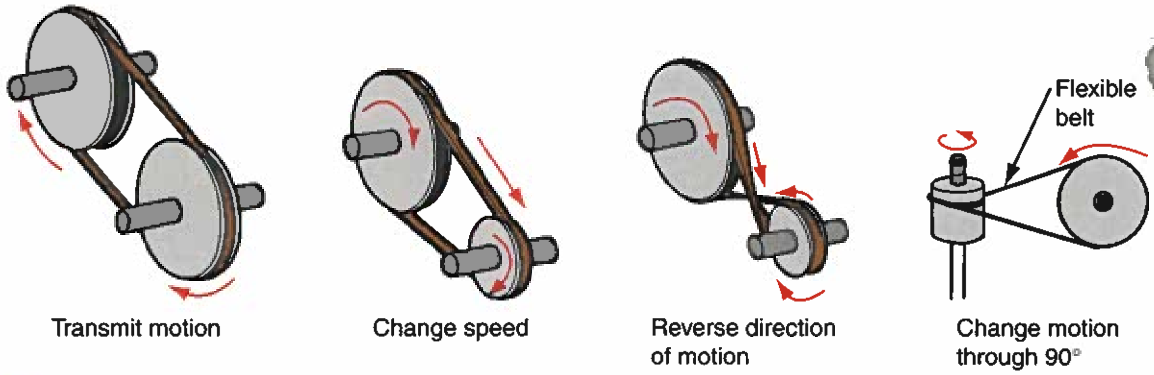


Figure 8-23. Pulleys can transmit motion from one point to another.

The Wheel and Axle

The *wheel and axle* is a simple machine that consists of a large diameter disk or wheel that is attached rigidly to a smaller diameter bar (axle). Effort applied to the outer edge of the wheel is transmitted through the axle. Think of it as a special kind of Class 1 lever. See **Figure 8-24**.

Like levers, the wheel and axle contains three elements: effort, fulcrum, and resistance. In the case of the doorknob, the effort is applied to the rim of the wheel (knob). The knob multiplies the effort and transmits it through the axle (bar). The resistance is the door latch.

Even the simple pizza cutter uses a wheel and axle. The effort is supplied by the person pressing on the handle and the resistance is the force of the wheel on the pizza. See **Figure 8-25**.

The Inclined Plane

There are at least two ways of loading the furniture onto the truck in **Figure 8-26**. One way is simply to lift it. However, it is much easier and safer to push the motorcycle up a sloping plank. The sloping surface formed by the plank is called an *inclined plane* or ramp.

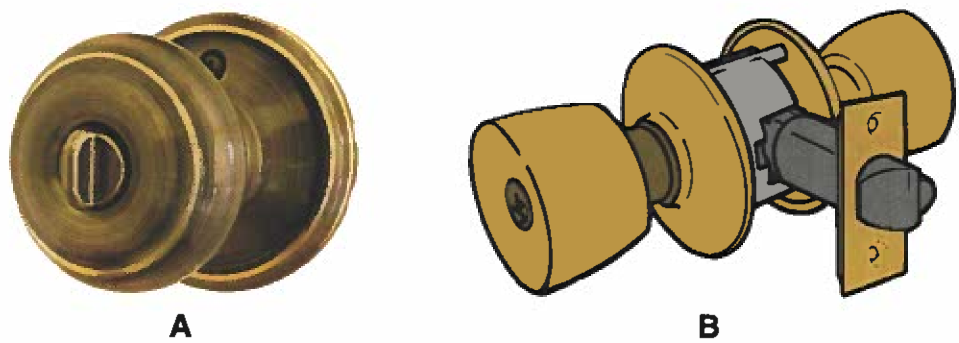


Figure 8-24. A—A doorknob is a common example of the wheel and axle. B—Where are the effort, fulcrum, and resistance?

Figure 8-25. A pizza cutter is a form of wheel and axle. Where are the effort, fulcrum, and resistance located?

Figure 8-26. It would be much more difficult to lift furniture in and out of the truck without a ramp. Would a shorter ramp make the task harder or easier?

Uses for Inclined Planes

Common uses for inclined planes include:

- Loading and unloading a car transporter.
- Replacing steps so people with strollers or wheelchairs have access.

Figure 8-27 shows other common uses for inclined planes.

Calculating Inclined Planes

How do people who build ramps decide about their length? Guessing about it is too costly. They might have to tear down the ramp and start over. Therefore, they use mathematics.

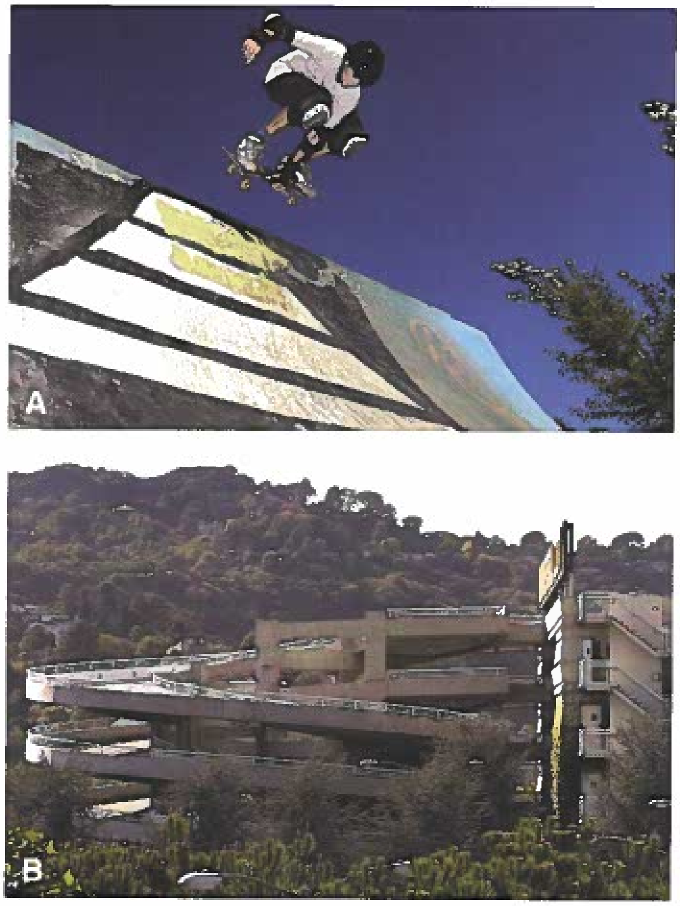


Figure 8-27. We use inclined planes for many purposes. A—Skilled skateboarders use ramps to perform various feats. B—Ramps provide access to multistory parking garages.

In general, heavier objects need longer ramps or more effort to move them upward: the more gradual the rise, the less effort required. We can say the length of the inclined plane is directly related to the mass of the object. This means that as mass increases, ramp length increases. **Figure 8-28** shows this relationship. So does the following formula:

Effort (E) × Effort Distance (ED) = Resistance (R) × Resistance Distance (RD)

Now, let us see how we might use the formula to work out a problem. Suppose, for example, that a mass of 450 lb. (200 kg) needs to be raised 6′ (2 m). Then suppose that the most force that can be exerted is 100 lb. (50 kg). How long must the ramp be so the force is able to move the object?

Formula:

$$ED = R \times \frac{RD}{E}$$

U.S. Customary calculation:

$$450 \times \frac{6}{100} = \frac{2700}{100} = 27'$$

Metric calculation:

$$200 \times \frac{2}{50} = \frac{400}{50} = 8 \text{ m}$$

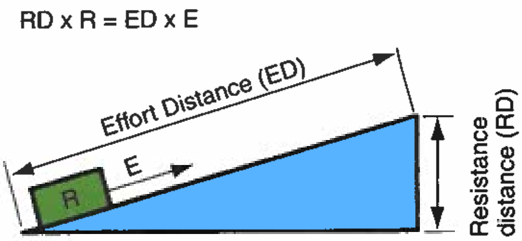


Figure 8-28. The mass of an object and the distance it is raised are related to the length of the inclined plane.

The Wedge

The *wedge* is a special version of the inclined plane, as shown in Figure 8-29. It is two inclined planes back-to-back.

The shape is effective because the force exerted pushes out in two directions as it enters the object. Do you see the difference between the wedge in Figure 8-29 and the inclined plane in Figure 8-28? Other applications of the wedge include the plow, a doorstop, the blade of a knife, and the prow of a boat. See Figure 8-30.

Figure 8-29. Because of its shape, an axe enters material easily and can split it apart.

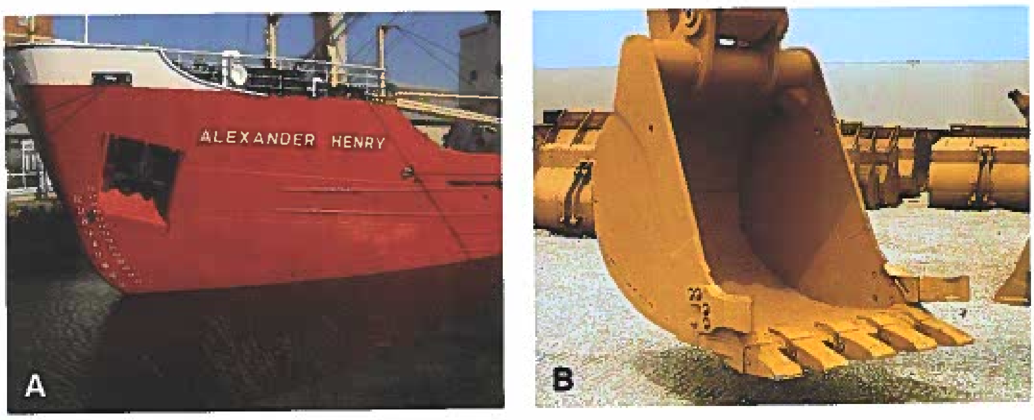


Figure 8-30. We use the wedge in many products. A—The wedge-shaped prow (front) of a ship cuts easily through the water. B—The teeth on the bucket of a backhoe are wedge-shaped to enter the soil more easily.

The Screw

A *screw* is an inclined plane wrapped in the form of a cylinder. To illustrate how this works, take a rectangular piece of paper and cut it along a diagonal. This triangle will remind you of an inclined plane. Now wrap it around a pencil. Roll from the edge of the triangle toward the point to shape it like a screw. See Figure 8-31.

When we examine the inclined plane, we find that the time taken for the load to be pushed up a longer inclined plane increases, but the effort decreases. The same is true in the case of the screw threads on a nut and bolt. The greater the number of threads, the shallower the slope, and the longer it takes to move the nut to the head of the bolt. However, a greater number of threads makes it easier to move the nut against a resistance.

The wedge-shaped section of a tapering wood screw reveals another application of the wedge. See Figure 8-32. It allows the screw to force its way into the wood.

Screw threads may be used in two quite different ways. They may be used to fasten, as with wood screws, machine screws, and light bulbs. They may also transmit motion and force. Examples are C-clamps, vises, and car jacks. See Figure 8-33. Note also that a screw converts rotary motion into straight-line motion. See Figure 8-34.

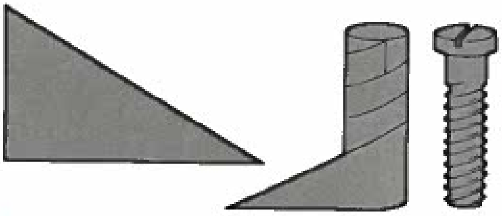
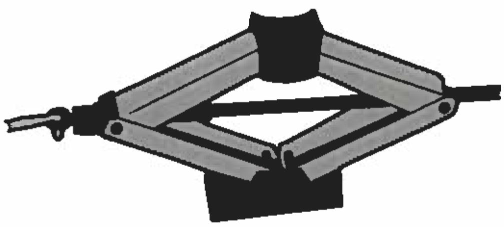


Figure 8-31. A screw is an inclined plane wrapped into a cylinder.

Figure 8-32. A wood screw also has a wedge shape to push aside the wood fibers as it enters the wood.

A



B

Figure 8-33. A—A scissor jack lifts heavy loads with less effort applied. B—As the screw of the jack is turned, the two ends of the jack are forced to move toward each other, and the car is raised.

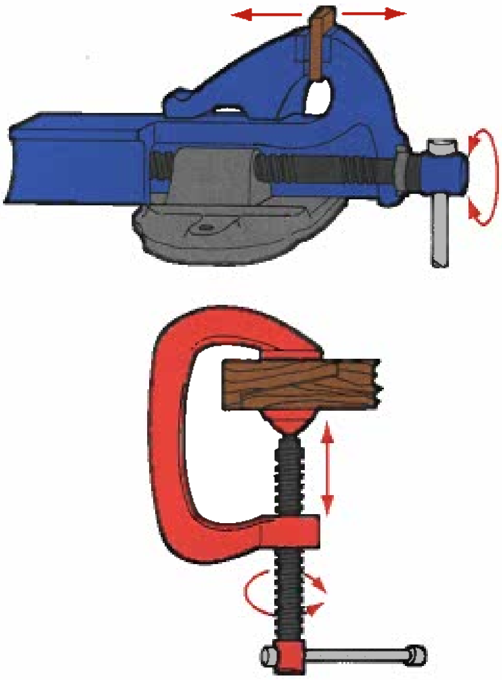


Figure 8-34. Screw threads are used on vises and C-clamps. They convert rotary motion to straight-line motion.

Gears

Gears are *not* classified as one of the six simple machines. They are similar to pulleys in that their motion is usually circular and continuous. However, gears have an advantage over pulleys. They cannot slip.

Many bicycles have gears to help make pedaling as effortless as possible. See Figure 8-35. When climbing hills, the cyclist selects a low gear to make pedaling easier. When descending a hill, the cyclist uses a higher gear that provides a high speed in return for slower pedaling.

A mechanical clock contains many different sized gear wheels. They are arranged so that they rotate the clock hands at different speeds.

Figure 8-35. Notice how gears are used in this bicycle. What is the advantage of using gears instead of pulleys?

Gears, like pulleys, are modified levers. They transmit rotary motion. They increase or decrease speed, change the direction of motion, or transmit a force. See **Figure 8-36.** This force, known as ***torque***, acts at a distance from the center of rotation. To understand this concept more easily, think of torque as a measure of turning effort. It is similar to using a wrench to tighten a bolt. See **Figure 8-37** and **Figure 8-38**.

An effort (E) is applied at a distance (R) from the center of the nut. The torque on the nut is calculated by multiplying the effort (E) by the distance (R). The applied force is measured in pounds (newtons) and the distance from the center of rotation is measured in feet. Therefore, torque is measured in ft.-lb. In the metric system, the applied force is measured in newtons, the distance from the center of rotation is measured in meters, and torque is measured in newton-meters (N•m).

As you look at a gear, you can consider the center of the gear to be like the nut. Consider the end of the gear tooth to be like the end of the wrench.

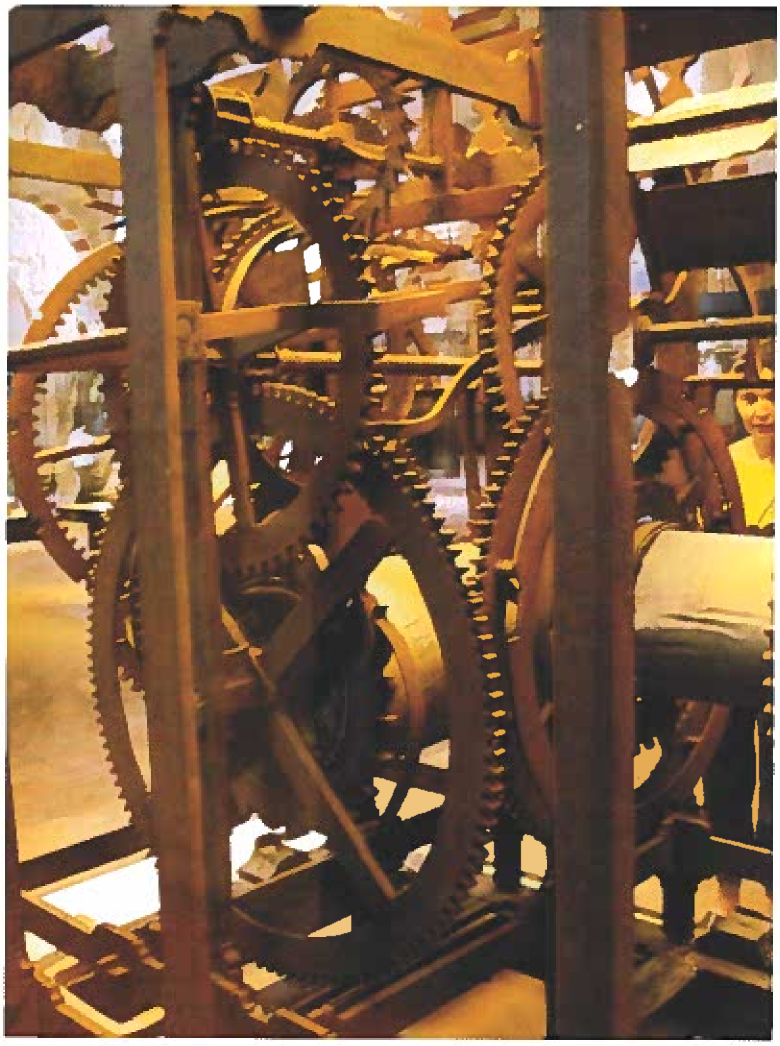


Figure 8-36. Gears are similar to pulleys, except they have teeth that prevent them from slipping.

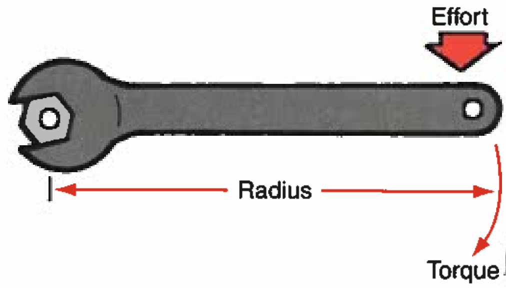


Figure 8-37. Torque is force applied to a radius.

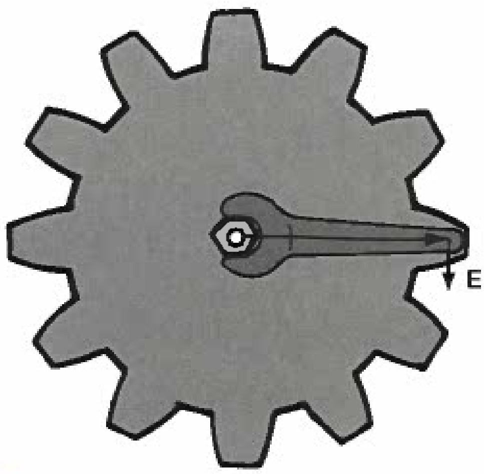


Figure 8-38. A gear can be compared to a wrench turning a nut. How is the gear similar to the wrench?

Gears are used in groups of two or more. A group of gears is called a *gear train. The gears in a train are arranged so that their teeth closely* interlock, or mesh.

When two gears are of the same size, they act as a simple torque transmitter. They both turn at the same speed, but in opposite directions, as shown in **Figure 8-39**. The input motion and force of the drive gear are applied to the driven gear. The driven gear transmits the output motion and forces.

When two gears are of different sizes, as shown in **Figure 8-40**, they act as torque converters. The larger gear is called a *wheel*. The smaller gear is called a *pinion*. The pinion gear revolves faster, but the wheel delivers more force.

Gear Calculations

The amount of torque delivered by a gear is described as a ratio. For example, suppose a gear that has 10 teeth meshes with a gear that has 30 teeth. The smaller gear will make three revolutions for each revolution of the larger gear. As the small gear makes one revolution, its 10 teeth will have meshed with 10 teeth on the larger gear. The large gear will have turned through ten-thirtieths or one-third of a revolution. The small gear has to make three revolutions to turn the large gear through one full revolution. The gear ratio is therefore 3:1. See **Figure 8-41**.

Gear trains are either simple or compound. In a simple gear train, there is only one meshed gear on each shaft. **Figure 8-42** shows an idler gear placed between the drive gear and the driven gear. The driver gear and the driven gear now rotate in the same direction. The idler gear does not change the gear ratio between the driver gear and the driven gear.

A compound gear train also has a drive gear and a driven gear. However, the intermediate gears are fixed together on one common shaft, as shown in **Figure 8-43**. The gear wheels on the intermediate shaft are not idlers, because one is a driven gear and the other is a drive gear. They do affect the ratio of the gear train.

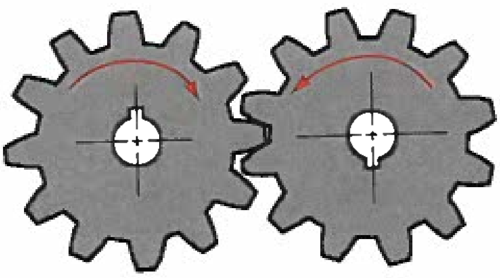


Figure 8-39. On a gear train, as one gear moves, its torque is transmitted to another gear.

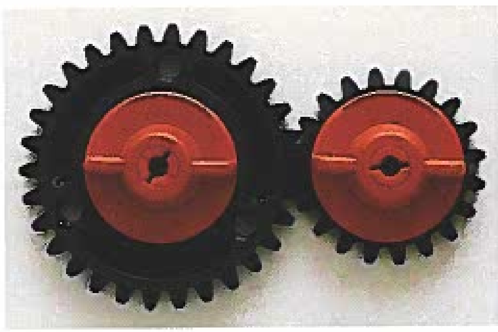


Figure 8-40. Two gears act like levers to convert torque.

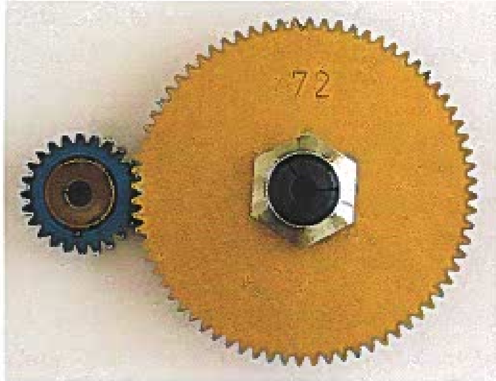


Figure 8-41. When a small gear drives a larger gear, the input torque is multiplied.

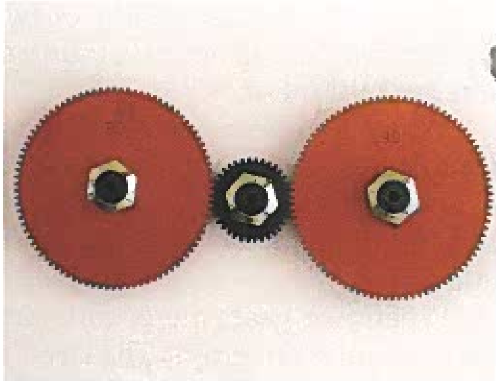
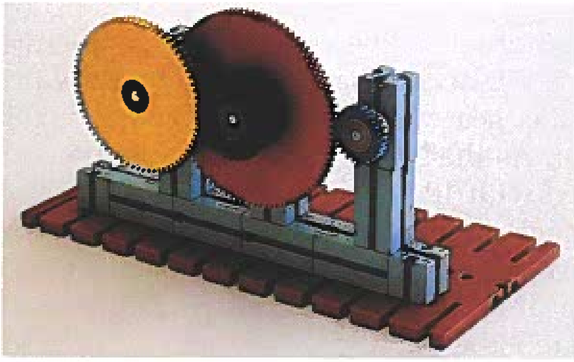


Figure 8-42. A simple gear train.

Figure 8-43. A compound gear train. Two gears are attached to the same shaft.



Just like the six simple machines, gears provide mechanical advantage. This advantage is calculated as follows:

$$\text{Mechanical Advantage (M.A.)} = \frac{\text{Number of Teeth on Driven Gear}}{\text{Number of Teeth on Driver Gear}}$$

The *velocity*, or speed, of the driven gear is calculated as follows:

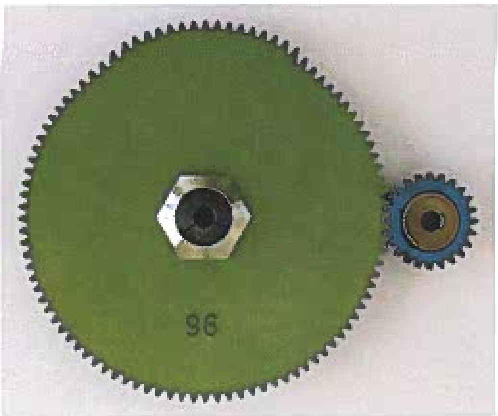
$$\text{Velocity of Driven Gear} = \text{Number of Teeth on Driver Gear} \times \frac{\text{Number of Teeth on Driver Gear}}{\text{Number of Teeth on Driven Gear}}$$

An example of these gear calculations is shown in **Figure 8-44**.

Types of Gears

Gears are designed in a variety of types for a variety of purposes. The five most common gear types are spur, helical, worm, bevel, and rack-and-pinion.

The spur gear is the simplest and most fundamental gear design. Its teeth are cut parallel to the center axis of the gear, as shown in **Figure 8-45**. The strength of spur gears is no greater than the strength of an individual tooth. Only one tooth is in mesh at any given time.



$$MA = \frac{96}{32} = \frac{3}{1} = 3$$

$$Velocity = \frac{32 \times 288}{96} = 96 \text{ rpm}$$

Figure 8-44. The mechanical advantage and the velocity of compound gears can be calculated as shown here.

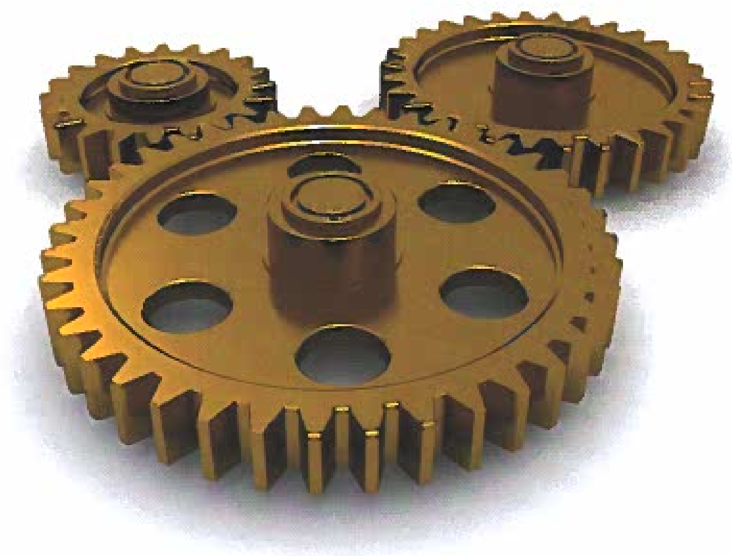


Figure 8-45. On spur gears, the teeth are cut straight across the width of the gears.

To overcome this weakness, helical gears are sometimes used, as shown in Figure 8-46. Since the teeth on helical gears are cut at an angle, more than one tooth is in contact at a time. The increased contact allows more force to be transmitted.

A worm is a gear with only one tooth. The tooth is shaped like a screw thread. A wormwheel meshes with the worm. See Figure 8-47. The wormwheel is a helical gear with teeth inclined so that they can engage with the threadlike worm. This system changes the direction of motion through 90°. It also has the ability to make major changes in mechanical advantage and speed. Input into the worm gear system is usually through the worm gear. A high mechanical advantage is possible because the helical gear advances only one tooth for each complete revolution of the worm gear. The worm gear in Figure 8-47 will rotate 40 times to turn the helical gear only once. This is a mechanical advantage of 40:1. Worm gear mechanisms are very quiet running.

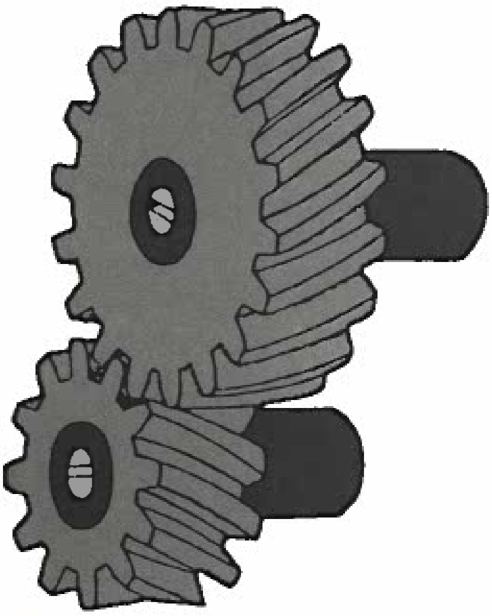


Figure 8-46. Helical gears, cut at an angle, allow several teeth to engage at one time.

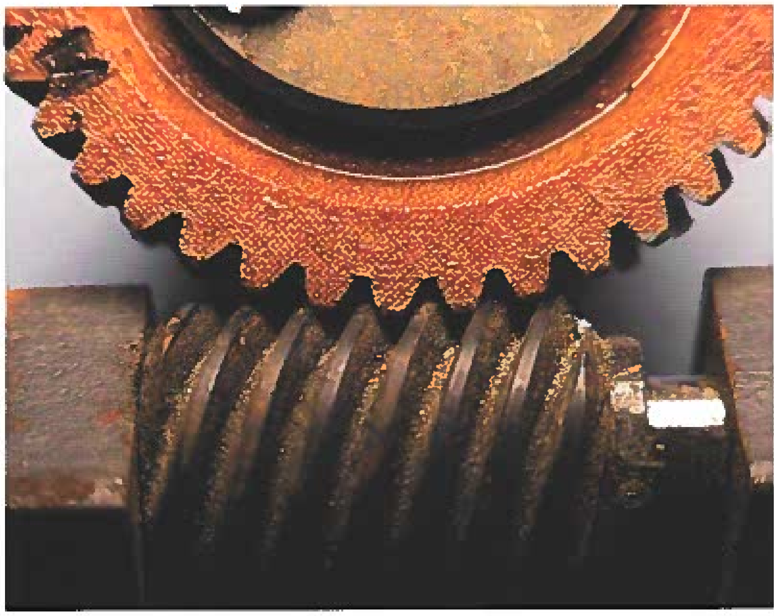


Figure 8-47. In a worm and worm wheel, the worm (bottom) has only one tooth. It spirals like a screw thread.

Bevel gears, Figure 8-48, change the direction in which the force is applied. This type of gear can be straight-cut like spur gears, or they may be cut at an angle, like helical gears.

Rack-and-pinion gears, Figure 8-49, use a round spur gear (the pinion). It meshes with a spur gear that has teeth cut in a straight line (the rack). The rack-and-pinion transforms rotary motion into linear (straight-line) motion and vice versa. Figure 8-50 shows two uses for rack-and-pinion gears.

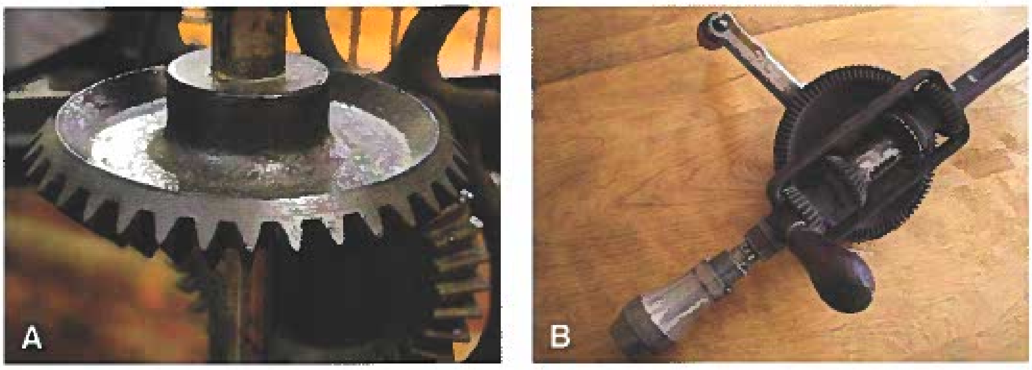


Figure 8-48. A—Bevel gears change the direction of the applied force. B—A hand drill uses bevel gears.

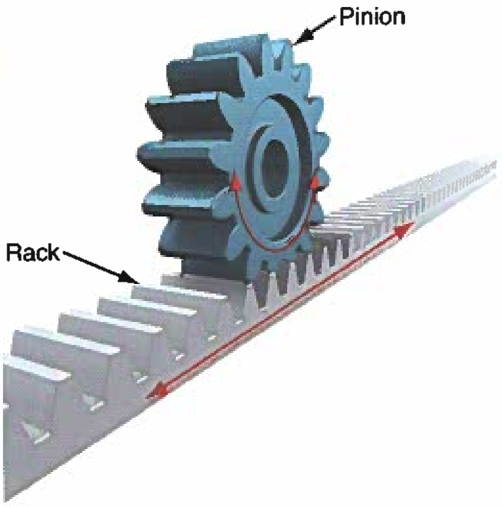


Figure 8-49. Rack-and-pinion gears convert rotary motion to straight-line motion.

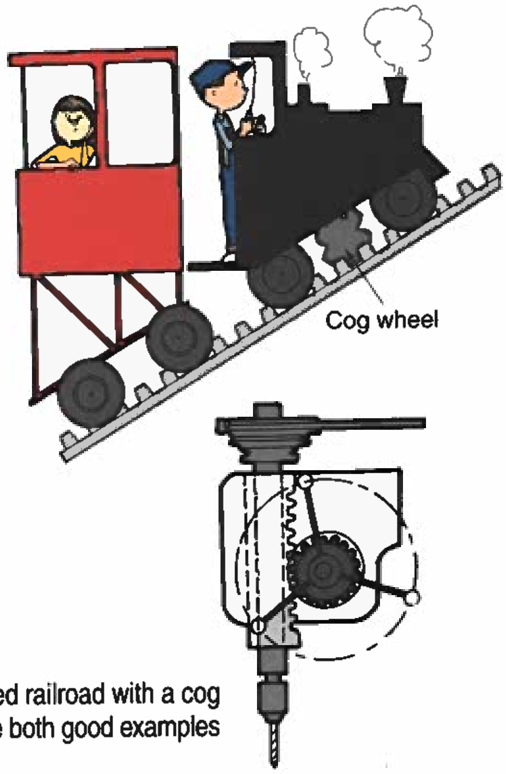


Figure 8-50. An inclined railroad with a cog wheel and a drill press are both good examples of rack-and-pinion gears.

Transmissions

A transmission provides gear shifting to allow an increase or decrease in speed without overworking either an engine in a vehicle or a human pedalling a bicycle. See **Figure 8-51**. If you are a cyclist, you know that it is very difficult for you to start in the highest gear. You must start out in a low gear and gradually change to higher gears so that the speed of pedalling remains relatively constant. The same is true for a car. Without a transmission, a car would not have enough power to accelerate from a standstill. When a transmission is in low gear, the engine has to turn several times to make the drive shaft and the wheels turn once. As the transmission moves through the gears, from low to high, the drive shaft and the engine turn at approximately the same speed. The vehicle speed increases and the engine speed drops.

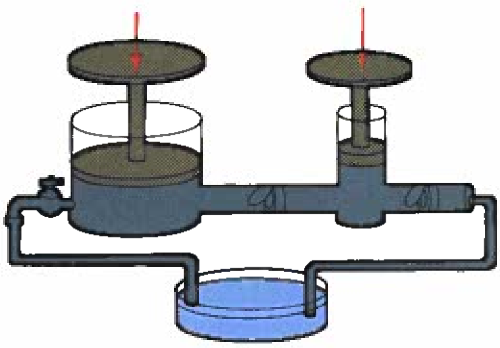
An automatic transmission performs the same function as a standard transmission, except that it shifts gears automatically by using internal oil pressure. A third type of transmission is a continuously variable transmission (CVT). This type uses belt systems to provide an infinite number of gear ratios. It improves engine efficiency by allowing the engine to match its speed to the load more efficiently. Currently there are also many other choices that are partly manual and partly automatic (automated manuals).

Figure 8-51. The gears on a multispeed bicycle allow you to decrease effort or increase speed. How is this like the transmission on an automobile?

Pressure

You have seen how simple machines and gears are able to move a greater resistance with a smaller effort. Now you will see that pressure can increase the effort applied. *Pressure* is the effort applied to a given area. **Figure 8-52A** shows a diagram of a simple system for multiplying force through use of pressure. **Figure 8-52B** shows a simple pressure device used to lift an automobile.

To understand how pressure can be increased, think about the area on which the effort presses. Would you rather a woman step on your foot with a small, pointed heel or with a larger, flat heel? See **Figure 8-53**. When a surface area is small, a little effort produces a large pressure.



A

B

Figure 8-52. Hydraulics use pressure to increase force. A—In a hydraulic system, a fluid transmits effort from where it is applied to where it is used. B—A hydraulic lift is used to support the mass of an automobile.

Figure 8-53. Imagine someone stepping on your foot. Which will hurt more, the pointed heel or the flat heel?

Calculating Pressure

To calculate pressure, divide effort by area. The formula is:

$$\text{Pressure} = \frac{\text{Effort}}{\text{Area}}$$

For example, if a 120-lb. woman rests her mass on a 4-in^2 heel, the pressure is 30 psi (pounds per square inch). On the other hand, if she rests her mass on a 1/4-in^2 heel, the pressure increases to 480 psi.

In the metric system, effort is measured in newtons. Area is measured in meters squared (m^2). Pressure is calculated in newtons per meter squared (N/m^2). The metric unit of measure for pressure is the pascal (Pa). Since a pascal is small, kilopascals are generally used (1 kPa = 1000 Pa).

Consider another example of how area affects pressure. A knife has a sharp edge. Pressed against a surface, it takes up a very small area. That is why it cuts: the material offers little resistance to such a tiny surface. A dinner fork works in a similar way. The narrow prongs place enough pressure on the food to pierce it easily.

Hydraulics and Pneumatics

The study and technology of the characteristics of liquids at rest and in motion is called *hydraulics*. *Pneumatics* is the study and technology of the characteristics of gases. Unlike solids, liquids and gases flow freely in all directions. Pressure, therefore, can be transmitted in all directions. For example, water will flow in a garden hose even when the hose is curved in many directions.

Figure 8-54 shows a model of a hydraulic lift. The effort is being applied to a piston. Pressure produced by the effort is being transmitted by the liquid to a second piston. This piston moves the resistance. The second piston has a larger area and so the pressure presses on a larger area. This produces a larger effort. If the resistance piston has four times the area of the effort piston, the effort on it will be four times greater.

From this example, you can see that the effort acting on a piston from a liquid under pressure depends on the area of the piston. The larger the area is, the larger the effort will be. However, the distance moved by the larger piston will be less than the distance moved by the smaller piston. In **Figure 8-54**, the smaller piston moves four times the distance of the larger piston.

The hydraulic brake system on passenger cars operates using the same principles as the hydraulic lift. See **Figure 8-55**. Using the brake pedal, a driver applies a small effort to the piston. Hydraulic fluid is transmitted through the brake lines to a larger piston. The larger piston forces the brake pads and shoes against the discs and drums. The brake systems of large trucks, buses, and trains are often pneumatically operated.

Among the many common applications of hydraulic power are dentist and barber chairs, door closers, and power steering. Common applications of pneumatic power include a variety of tools such as air drills, screwdrivers, and jackhammers. Sometimes hydraulic and pneumatic systems are combined. For example, air pressure forces hydraulic fluid to raise the lift in a garage, as shown in **Figure 8-52B**.

Because of their many advantages, most industries use hydraulic and pneumatic systems. These advantages include the ability to:

- Multiply a force using minimal space
- Transmit power to wherever pipe, hose, or tubing can be located
- Transmit motion rapidly and smoothly
- Operate with less breakage than occurs with mechanical parts
- Transmit effort over considerable distance with relatively small loss

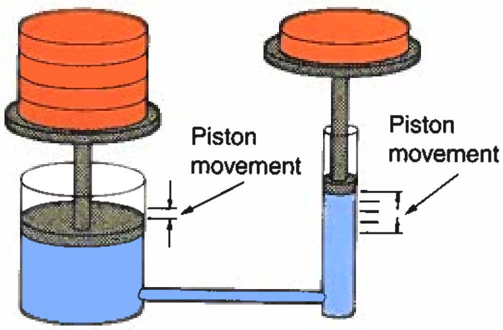


Figure 8-54. In this hydraulic lift, the large movement in the piston on the right causes a smaller movement in the piston on the left. Why is this an advantage?

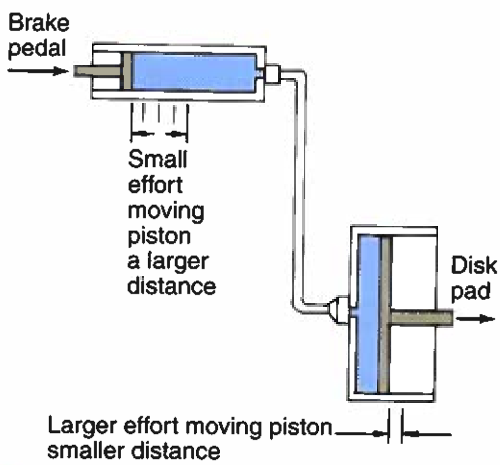


Figure 8-55. An automobile braking system is an example of a hydraulic system.

Mechanism

A *mechanism* is a way of changing one kind of effort into another kind of effort. For example, a C-clamp holds two pieces of wood together while glue sets. Rotary motion in the screw is changed to linear motion to apply pressure. See **Figure 8-56**.

Mechanisms can be combined to form machines. Their advantages include:

- Changing the direction of an effort
- Increasing the amount of effort applied
- Decreasing the amount of effort applied
- Applying an effort to a place that is otherwise hard to reach
- Increasing or decreasing the speed of an operation

Machines change one kind of energy into another and do work. The amount of *work* done is approximately equal to the amount of energy changed.

Work = (Energy Change)
= Effort × Distance Moved in Direction of Effort

For example, how much work is done to move a 50 lb. resistance a distance of 5′?

Work = 50 × 5
= 250 ft.-lb.

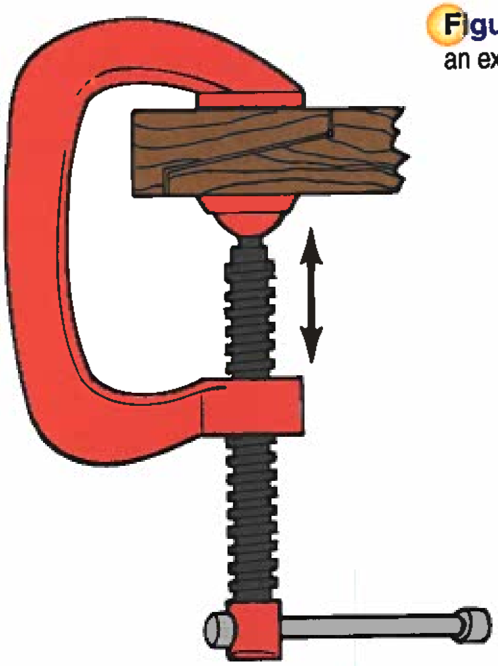


Figure 8-56. A C-clamp is an example of a mechanism.

In metric, how much work would be done to move a 50 N resistance through 4 meters?

$$\text{Work} = 50 \times 4 = 200 \text{ joules}$$

Machines make it easier to do work. However, no machine does as much work as the energy put into it. If a machine did the same amount of work as the energy supplied, it would be 100% efficient. Most machines lose energy as heat or light. Approximate efficiencies of some common machines are listed in **Figure 8-57**.

Another important term associated with work is power. ***Power*** is the rate at which work is done or the rate at which energy is converted from one form to another. It can also be the rate at which energy is transferred from one place to another. Power can be expressed in this formula:

$$\text{Power} = \frac{\text{Work}}{\text{Time}} \qquad P = \frac{W}{T}$$

Mechanisms use or create motion. See **Figure 8-58**. The four basic kinds of motion are:

- Linear—straight-line motion
- Rotary—motion in a circle
- Reciprocating—backward and forward motion in a straight line
- Oscillating—backward and forward arc motion, like a pendulum

Mechanisms are often used to change one kind of motion into another kind. Some examples are shown in **Figure 8-59**.

Friction

Friction is a force that acts like a brake on moving objects. Your finger will slide without much effort on a pane of glass. But if you do the same thing on sandpaper, you can feel a resistance slowing your movement.

Figure 8-57. Scientists, engineers, and manufacturers are always trying to design more efficient engines, motors, and machines.

Watt's Steam Engine	3%
Modern Steam Engine	10%
Gasoline Engine	30%
Nuclear Power Plant	30%
Aircraft Gas Turbine	36%
Diesel Engine	37%
Rocket Engine	48%
Electric Motor	80%

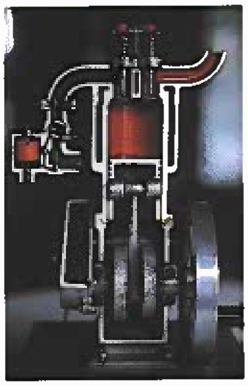
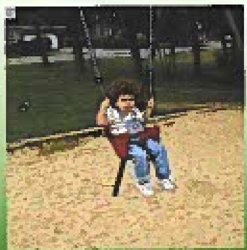
Motion	Application	Symbol
Linear		
Rotary		
Reciprocating		
Oscillating		

Figure 8-58. Mechanisms are used to create different kinds of motion.

Friction helps us in many ways. Without friction, cars would skid off the road and nails would pop out of walls. Friction also enables us to walk on most surfaces without sliding. But it can also slow us down and produce unwanted heat. When you pedal your bicycle, you are working against friction.

The moving parts of mechanisms do not have perfectly smooth surfaces. The tiny projections on the surfaces rub on one another. This creates friction and results in heat. The friction between the moving parts must be minimized so that:

- Less energy will be needed to work the machine
- Wear and tear will be reduced
- Moving parts will stay cooler

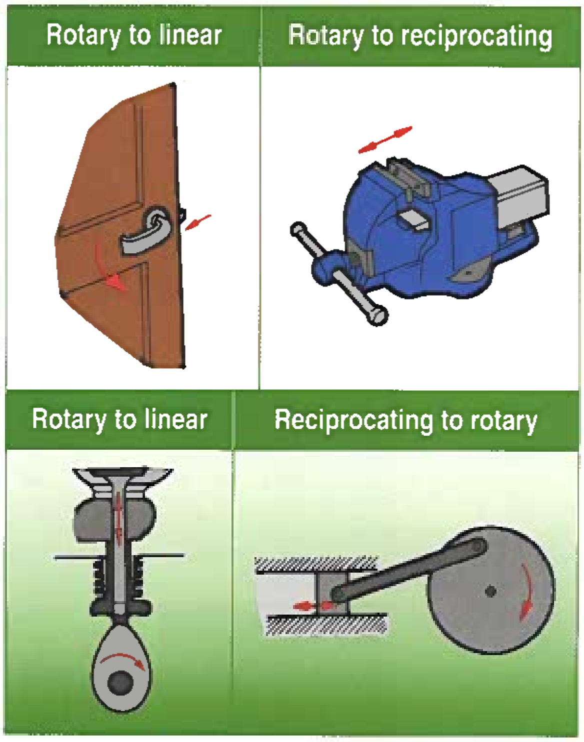


Figure 8-59. Mechanisms change motion from one form to another.

Reducing Friction

Friction may be reduced in several ways, as shown in Figure 8-60 through Figure 8-62.

- Ball bearings—steel balls enable surfaces to roll over one another instead of sliding.
- Air or water cushions—compressed air or water separates moving parts.
- Streamlining—the shape of a fast-moving object can be changed to reduce its resistance to air or water.

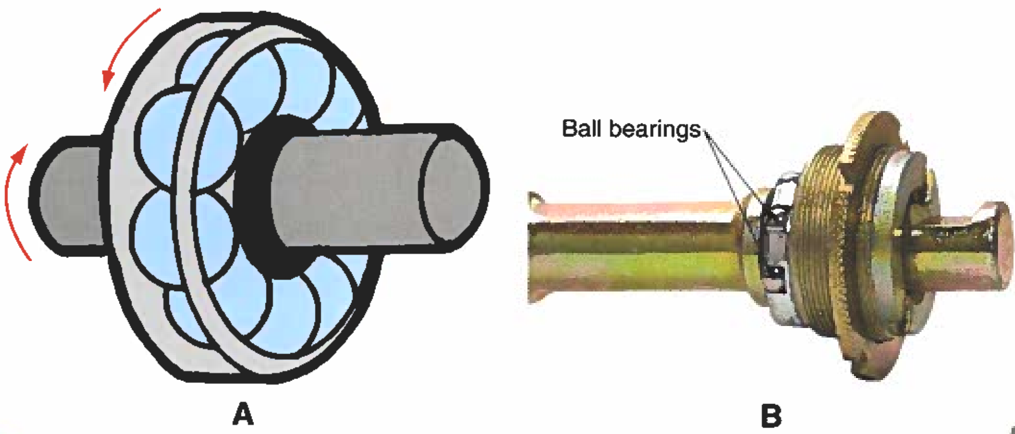


Figure 8-60. A—Ball bearings allow parts to roll over one another, reducing friction. B—The bearings in this shaft are separated to provide more structural stability to the product.

Figure 8-61. Hovercraft use a cushion of air to reduce friction.

Figure 8-62. One of the effects of streamlining is to reduce air drag, which is a form of friction.

Friction may also be reduced in other ways. In the game of curling, for example, "sweeping" the ice in front of the rock makes the rock travel further and curl less. The heat from the sweeping action melts the ice, creating a micro-thin layer of water on which the rock can ride. Sweeping can increase the distance a rock travels by several feet. See **Figure 8-63**.

Lubrication

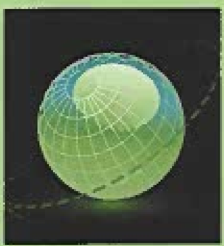
If you rub your hands together quickly, you will feel heat build up. That heat is caused by friction. If your two hands were coated with oil, friction would be reduced so they could more easily slide against one another. *Lubrication* is the application of a smooth or slippery substance between two objects to reduce friction.

Figure 8-63. Sweeping melts the ice in front of the rock. Why does this make the rock travel further?

Oil separates two surfaces that would otherwise touch, rub, and wear each other away. See Figure 8-64. For good lubrication, oil must have the right *viscosity* (thickness). Viscosity is a kind of friction in liquids. It is caused by the molecules of a liquid rubbing together. Water has a low viscosity and pours easily. Honey and molasses have a high viscosity, so they ooze out of containers. Heating honey and some oils will cause them to flow more easily.

Motor oil becomes thinner (less viscous) as its temperature increases. In the warm summer months, a thicker oil is needed. However, in the icy cold of a winter's morning, a thinner oil is needed for easier starting. Therefore, multi-grade oils have been developed to meet the needs of automobile engines in a range of temperatures.

Figure 8-64. Oil lubricates parts to reduce friction.



Think **Green**

Green Lubrication

Lubricants such as the motor oil used in vehicles are necessary, but they are not environmentally friendly. Motor oil is not biodegradable, and in some states, it is considered a hazardous waste. Automobile technicians are required to recycle used oil and to document the process. Individuals who change the oil in their vehicles should take the used oil to collection sites for recycling.

New alternatives to traditional motor oil are becoming available, however. Argonne National Laboratory has used nanotechnology to improve traditional motor oils. They combine extremely small particles of boric acid with motor oils. Each particle of boric acid is only 50 nanometers in diameter—less than one-thousandth the width of a human hair.

The resulting product is biodegradable, is not a health or environmental hazard, and does a better job of reducing friction than traditional motor oil. Engines that have less friction to overcome are more efficient and use less gasoline. Also, lowering friction can extend the life of the lubricated parts. Finally, these lubricants only have to be changed every 100,000 miles, so the vehicle owner spends less time and money changing the oil.

End Note

Over the centuries, humans have created many kinds of machines to make their work easier. From the six simple machines to today's complex computer systems, machines continue to help us in both work and leisure activities.

In the past few decades, computers have become much smaller and "smarter." At the same time, we have learned more about how humans think and reason. This information has been combined to make "intelligent" machines such as a robot that can vacuum the floor without guidance. Intelligent machines are just beginning to be widely used, but their possible uses are almost endless. Computer algorithms (sets of programming rules) are allowing computers to make more and more complex decisions.

What machines might people create in the next 50 years? How will they compare to the machines and mechanisms included in this chapter? You will have a part in deciding the answers to these questions. As you do, be sure to keep in mind the responsibilities that go along with invention. The machines created in this century and their effects on humans and the environment will help shape the world you live in.

Summary

- The six simple machines are the lever, pulley, wheel and axle, inclined plane, wedge, and screw.
- Gears are modified levers used in the transmission of rotary motion. They can increase or decrease speed, change the direction of motion, or transmit a force.
- Pressure can be used to increase an effort applied. Pressure in liquids is called *hydraulics*, and pressure in gases is called *pneumatics*.
- Mechanisms change one kind of effort into another kind of effort. They can be combined to form a machine. Machines change one kind of energy into another kind and do work.
- Friction results from resistance between the surfaces of moving parts. Lubrication and other methods can be used to reduce friction and increase the efficiency of machines.

Reading Target

Finding the Meaning of Unknown Words

Copy the following graphic organizer onto a separate sheet of paper. In the left column, record words from the chapter that you do not understand. As you read the chapter, try to guess their meanings and record your guesses in your chart. After you have read the chapter, look up each word in a dictionary. How close were your guesses? After you look up each word, go back and reread that portion of the chapter. Do you understand the chapter better?

Unknown Word	What I Think the Word Means	Dictionary Definition

Test Your Knowledge

Write your answers to these review questions on a separate sheet of paper.

1. When you hit a ball with a baseball bat, the bat is an example of a lever. Explain why.
2. Explain which of the following is an example of a Class 1 lever, and why: nutcracker, wheelbarrow, hockey stick, scissors.
3. A lever is used to move a load of 1500 newtons with a force of 300 newtons. What is the mechanical advantage of the lever?
4. A laborer using a Class 1 lever places the load the same distance from the fulcrum as the effort. If the fulcrum is moved closer to the load, what happens to the mechanical advantage?
5. What force would be required to raise a load of 15 newtons using a single, movable pulley?
6. List three examples of a wheel and axle.
7. List three practical applications of an inclined plane.
8. A 100 N load has to be moved to the top of an inclined plane that is 10 m long and 2 m high. What effort is required?
9. Explain the difference between a wedge and an inclined plane.
10. What is the connection between an inclined plane and a screw thread?
11. A gear is a modified form of which simple machine?
12. Describe three common uses for gears.
13. The wheel in a two-gear train has 60 teeth, and the pinion has 15 teeth. What is the ratio of the gear train?
14. Sketch a simple gear train in which the first and last gears are rotating in the same direction. Use arrows to show the direction of rotation of each gear.
15. How is pressure calculated?
16. What is the difference between hydraulics and pneumatics?
17. What is the difference between work and power?
18. Name the four basic kinds of motion and give one practical example of each.
19. List two benefits and two disadvantages of friction.
20. List three ways in which the friction between two objects can be reduced.

Critical Thinking

1. Gears are considered an improvement over pulleys because the teeth on a gear prevent a belt or chain from slipping. Why, then, are pulleys still in use today?
2. Which would work better for lubricating a rusty lock so that a key turns in it more easily: an oil with high, low, or medium viscosity? Why?

Apply Your Knowledge

1. Design and build a robotic arm that will move an AA dry cell from one location to another. Use syringes and tubing in your design.
2. Design and build a mechanism that will make a loud noise. Your solution must contain at least two simple machines.
3. Design and build a method of measuring the mass of a series of weights from 1 oz (25 g) to 16 oz (500 g).
4. Consult your library or the Internet (www.macchinedilenoardo.com) to learn about the mechanical inventions of Leonardo da Vinci. Which of his mechanical inventions are somewhat similar to the machines and vehicles we see today? Write a technical report explaining how innovations have been made to his machines over time to arrive at the products we use today. Evaluate the innovations that have been made. How did each innovation meet the needs of people at the time?
5. Research green alternatives to lubricants that are available in your area. Analyze each option to determine its advantages and disadvantages. Prepare a slide show or multimedia presentation and present it to the class to share the information you have found.
6. Research the principles of an atomic clock. Use library and Internet sources to find manuals that explain how an atomic clock works, or talk with people who are experienced in working with or repairing these clocks. Write a technical report explaining how atomic clocks work and describing any shortcomings or features you think can be improved.
7. Research one career related to the information you have studied in this chapter. Create a report that states the following:
   - The occupation you selected
   - The education requirements to enter this occupation
   - The possibilities for promotion to a higher level
   - What someone with this career does on a daily basis
   - The earning potential for someone with this career

   You might find this information on the Internet or in your library. If possible, interview a person who already works in this field to answer the five points. Finally, state why you might or might not be interested in pursuing this occupation when you finish school.

Apply Your Knowledge *(Continued)*

8. Changing technology often results in changing career opportunities. Think about the machines described in this chapter and research how they have been modified, improved, or built upon to create new machines through the last 200 years. Write an essay explaining how these modifications have affected career opportunities in technology.
9. Search the Internet to find the lubrication and maintenance specifications for several large machines. Write a report to explain your findings. Include answers to the following questions: What tasks are necessary to keep the machines running smoothly? What might happen if the maintenance schedule is not followed?

STEM Applications

1. **ENGINEERING** Go to www.rubegoldberg.com and look at the examples of some of his complicated mechanisms that do simple tasks. Then create your own "Rube Goldberg" mechanism that will rake leaves from a lawn or park area and place them in a bag. Your mechanism must use all six simple machines at least once.
2. **ENGINEERING** The Americans with Disabilities Act (ADA) provides guidelines for wheelchair ramps in public buildings. According to the ADA, ramp slopes should be between 1:16 and 1:20. The ramp should be at least 36 inches wide, and level landings must be provided at both ends. The landings must be at least as wide as the ramp and a minimum of 60 inches long. If two or more ramps are used together, the landings between the ramps must be at least 60 inches × 60 inches. Using these guidelines, design a ramp to allow wheelchair access to a theater stage that is 8 feet high. Create dimensioned working drawings to show the specifics of your design.

Simple machines help people relax and stay fit. How many simple machines can you identify in this exercise equipment?

CHAPTER 9

Transportation

The Bikedispenser allows one-way trips to other rental stations.

Better by Design

Hans Schreuder designed the Bikedispenser®

Hans Schreuder, a Dutch industrial designer, wants to encourage more people to use public transportation. Hans and his team noted that a lot of people use a bicycle to travel between their home and a train station. But when they arrive at their destination, they have to use a bus or taxi, both of which are expensive and add to air pollution, to complete their commute. The Bikedispenser is a fully automated public bicycle rental system. It can store 50–100 bicycles in a compact and safe environment at a train or bus station. You rent a bicycle, cycle to work and leave the bicycle in the company parking lot. At the end of the day, you cycle back to the station and return the bicycle to the Bikedispenser. Not only does this reduce the use of polluting buses, but cycling is healthier and often quicker than using public transportation.

Bicycle rental systems can have a positive effect on the environment. What are the environmental advantages and disadvantages?

"We must create better alternatives to those imperfect solutions currently in use, such as cars."