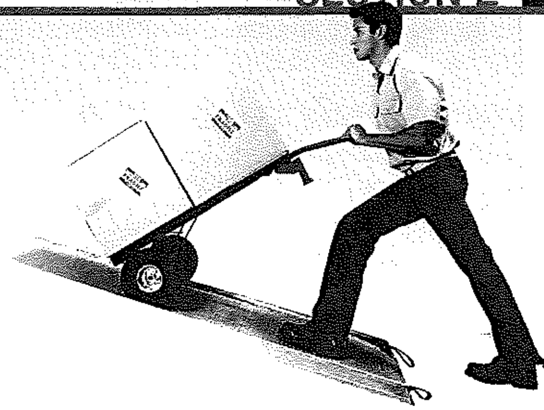
SECTION 2 Machines



PHYSICS 4 YOU When you think of the word *machine,* you might think of vacuum cleaners, computers, or industrial equipment. However, ramps, screws, and crowbars are also considered machines.

MAIN IDEA

Machines make tasks easier by changing the magnitude or the direction of the force exerted.

Essential Questions

- What is a machine, and how does it make tasks easier?
- How are mechanical advantage, the effort force, and the resistance force related?
- What is a machine's ideal mechanical advantage?
- What does the term efficiency mean?

Review Vocabulary

work a force applied through a distance

New Vocabulary

machine
effort force
resistance force
mechanical advantage
ideal mechanical advantage
efficiency
compound machine

Benefits of Machines

Machines, whether powered by engines or people, make tasks easier. A **machine** is a device that makes tasks easier by changing either the magnitude or the direction of the applied force. Consider the bottle opener in **Figure 10.** When you lift the handle, you do work on the opener. The opener lifts the cap, doing work on it. The work you do is called the input work (W_i). The work the machine does is called the output work (W_o).

Recall that work transfers energy. When you do work on the bottle opener, you transfer energy to the opener. The opener does work on the cap and transfers energy to it. The opener is not a source of energy. So, the cap cannot receive more energy than what you put into the opener. Thus, the output work can never be greater than the input work. The machine only aids in the transfer of energy from you to the bottle cap.

Mechanical advantage The force exerted by a user on a machine is called the **effort force** (F_e). The force exerted by the machine is called the **resistance force** (F_r). For the bottle opener in **Figure 10,** F_e is the upward force exerted by the person using the bottle opener and F_r is the upward force exerted by the bottle opener. The ratio of resistance force to effort force $\left(\frac{F_r}{F_e}\right)$ is called the **mechanical advantage** (MA) of the machine.

MECHANICAL ADVANTAGE

The mechanical advantage of a machine is equal to the resistance force divided by the effort force.

$$MA = \frac{F_r}{F_e}$$

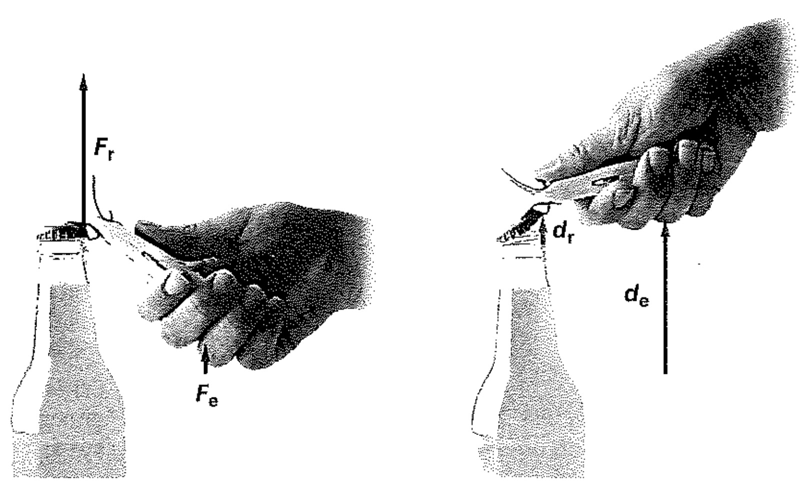


Figure 10 This bottle opener makes opening a bottle easier. However, it does not lessen the energy required to do so.

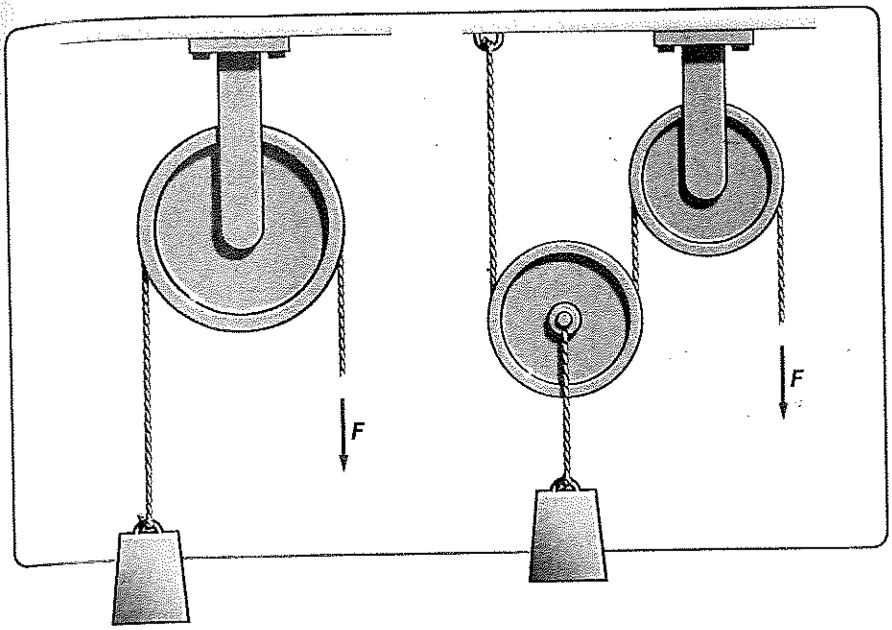


Figure 11 A fixed pulley has a mechanical advantage equal to 1 but is useful because it changes the direction of the force. A pulley system with a movable pulley has a mechanical advantage greater than 1, making the force applied to the object larger than the force originally exerted.

Watch a **BrainPOP video about pulleys.**

Video

For a fixed pulley, such as the one shown on the left in **Figure 11,** the effort force (F_e) and the resistance force (F_r) are equal. Thus, *MA* is 1. What is the advantage of this machine? The fixed pulley is useful, not because the effort force is lessened, but because the direction of the effort force is changed. Many machines, such as the bottle opener shown in **Figure 10** and the pulley system shown on the right in **Figure 11,** have a mechanical advantage greater than 1. When the mechanical advantage is greater than 1, the machine increases the force applied by a person.

☑ READING CHECK **Calculate** A machine has a mechanical advantage of 3. If the input force is 2 N what is the output force?

Ideal mechanical advantage A machine can increase force, but it cannot increase energy. An ideal machine transfers all the energy, so the output work equals the input work: $W_o = W_i$. The input work is the product of the effort force and the displacement the effort force acts through: $W_i = F_e d_e$. The output work is the product of the resistance force and the displacement the resistance force acts through: $W_o = F_r d_r$. Substituting these expressions into $W_o = W_i$ gives $F_r d_r = F_e d_e$. This equation can be rewritten $\frac{F_r}{F_e} = \frac{d_e}{d_r}$.

Recall that mechanical advantage is given by $MA = \frac{F_r}{F_e}$. Thus, for an ideal machine, **ideal mechanical advantage** (*IMA*) is equal to the displacement of the effort force divided by the displacement of the resistance force. *IMA* can be represented as follows.

PhysicsLAB

LIFTING WITH PULLEYS

How does the arrangement of a pulley system affect its ideal mechanical advantage.

iLab Station

IDEAL MECHANICAL ADVANTAGE

The ideal mechanical advantage of a machine is equal to the displacement of the effort force divided by the displacement of the resistance force.

$$IMA = \frac{d_e}{d_r}$$

Notice that you measure the displacements to calculate the ideal mechanical advantage, but you measure the forces exerted to find the actual mechanical advantage.

View an **animation on the benefits of machines.**

Concepts In Motion

VOCABULARY
Science Usage v. Common Usage

Efficiency
- Science usage

the ratio of output work to input work

The efficiency of the system of pulleys is 86 percent.

- Common usage

production without waste

The new, high-efficiency washing machine uses less water and electricity than an older machine.

Efficiency In a real machine, not all of the input work is available as output work. Energy removed from the system through heat or sound means that there is less output work from the machine. Consequently, the machine is less efficient at accomplishing the task. The **efficiency** of a machine (e) is defined as the ratio of output work to input work.

EFFICIENCY

The efficiency of a machine (in %) is equal to the output work, divided by the input work, multiplied by 100.

$$e = \frac{W_o}{W_i} \times 100$$

An ideal machine has equal output and input work, $\frac{W_o}{W_i} = 1$, and its efficiency is 100 percent. All real machines have efficiencies of less than 100 percent.

Efficiency can be expressed in terms of the mechanical advantage and ideal mechanical advantage. Efficiency, $e = \frac{W_o}{W_i}$, can be rewritten as follows:

$$e = \frac{W_o}{W_i} = \frac{F_r d_r}{F_e d_e}$$

Because $MA = \frac{F_r}{F_e}$ and $IMA = \frac{d_e}{d_r}$, the following expression can be written for efficiency.

EFFICIENCY

The efficiency of a machine (in %) is equal to its mechanical advantage, divided by the ideal mechanical advantage, multiplied by 100.

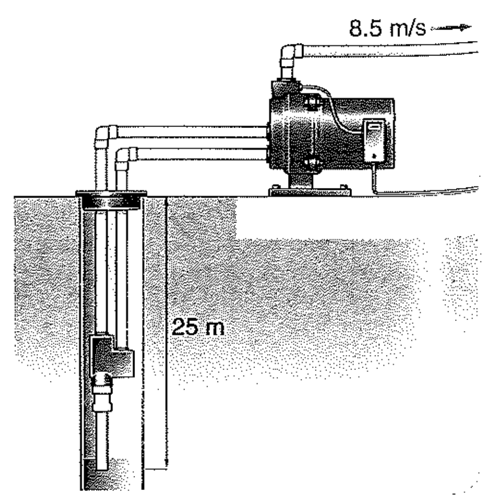
$$e = \left(\frac{MA}{IMA}\right) \times 100$$

A machine's design determines its ideal mechanical advantage. An efficient machine has an *MA* almost equal to its *IMA*. A less-efficient machine has a small *MA* relative to its *IMA*. To obtain the same resistance force, a greater force must be exerted in a machine of lower efficiency than in a machine of higher efficiency.

READING CHECK Determine If a machine has an efficiency of 50 percent and an *MA* of 3, what is its *IMA?*

PHYSICS CHALLENGE

An electric pump pulls water at a rate of 0.25 m^3/s from a well that is 25 m deep. The water leaves the pump at a speed of 8.5 m/s.



1. What power is needed to lift the water to the surface?
2. What power is needed to increase the water's kinetic energy?
3. If the pump's efficiency is 80 percent, how much power must be delivered to the pump?

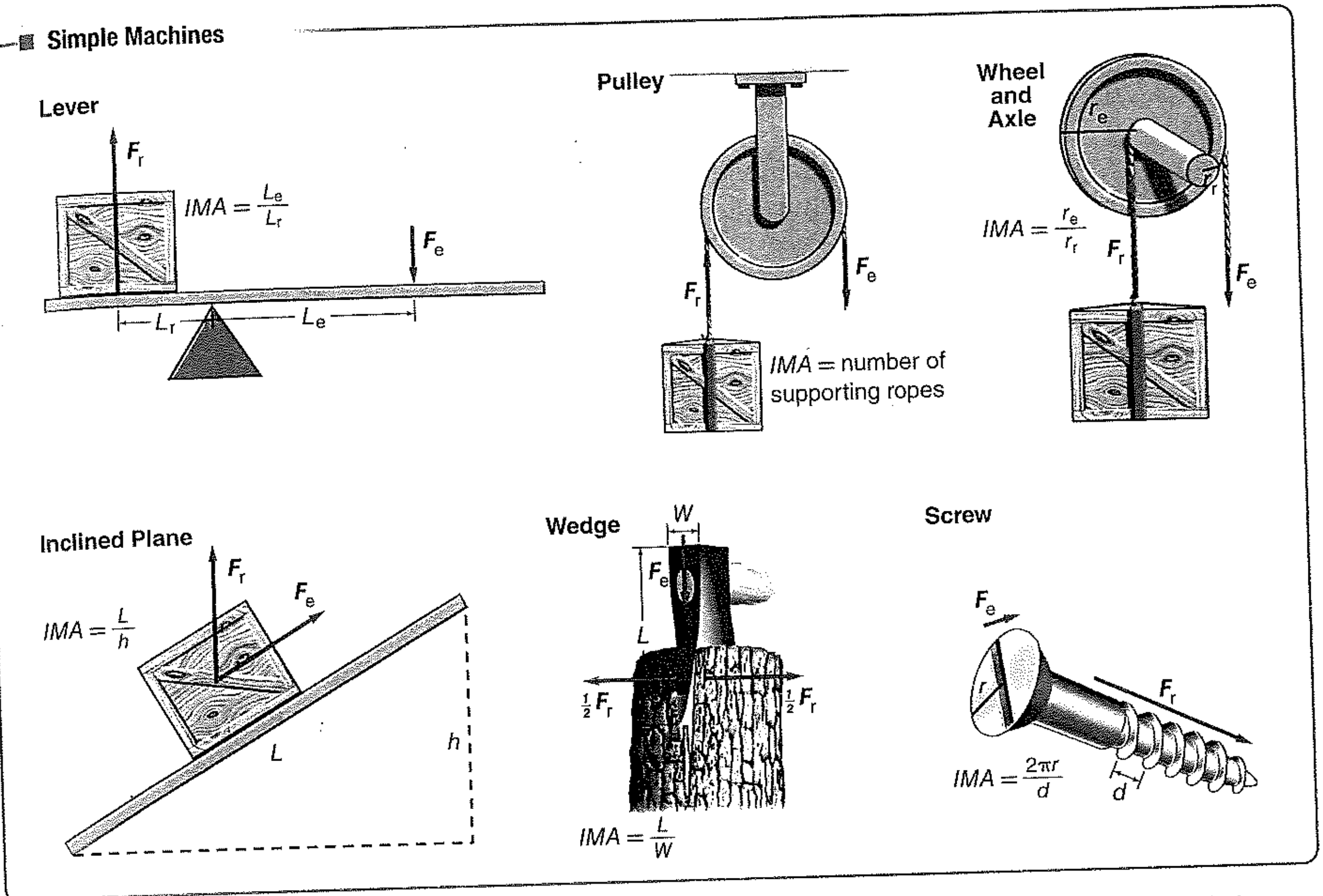


Figure 12 Each type of simple machine makes work easier by changing the direction or magnitude of the force. Notice that the *IMA* of each machine is related to the properties of the machine. For example, the *IMA* of a lever is equal to the length of the effort arm (L_e) divided by the length of the resistance arm (L_r). Similarly, the *IMA* of a wedge is equal to its length (L) divided by its width (W).

Identify an everyday example of each simple machine.

Compound Machines

Most machines, no matter how complex, are combinations of one or more of the six simple machines: the lever, pulley, wheel and axle, inclined plane, wedge, and screw. These machines are shown in **Figure 12.**

The *IMA* of each machine shown in **Figure 12** is the ratio of the displacement of the effort force to the displacement of the resistance force. For machines such as the lever and the wheel and axle, this ratio can be replaced by the ratio of the displacements between the place where the force is applied and the pivot point. A common version of the wheel and axle is a steering wheel, such as the one shown in **Figure 13.** The *IMA* is the ratio of the radii of the wheel and axle.

A machine consisting of two or more simple machines linked in such a way that the resistance force of one machine becomes the effort force of the second is called a **compound machine.** Some examples of compound machines are scissors (wedges and levers) and wheelbarrows (lever and wheel and axle).

READING CHECK Compare and contrast simple machines and compound machines.

Figure 13 A steering wheel is an example of a wheel and axle. Its *IMA* is $\frac{r_e}{r_r}$.

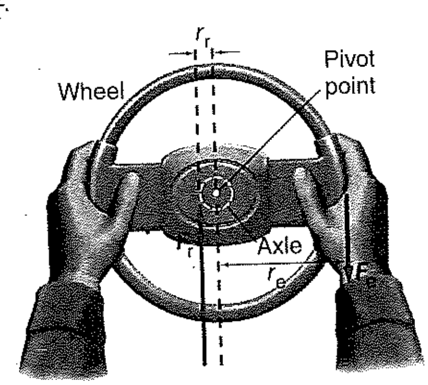
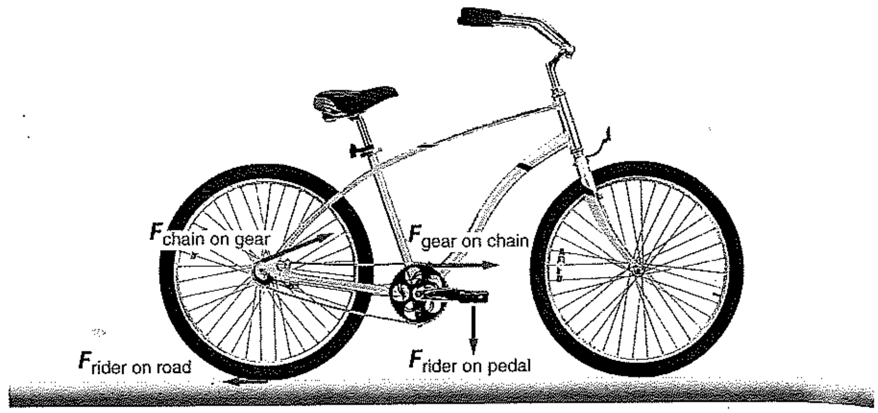


Figure 14 A bicycle is a compound machine. The rider exerts a force on the pedals, which exert a force on the chain. The chain then exerts a force on the rear gear.



MiniLAB

WHEEL AND AXLE

The gear mechanism on your bicycle multiplies the distance that you travel, but what does it do to the force you exert?

Mechanical advantage and bicycles A bicycle, such as the one shown in **Figure 14,** is a compound machine, consisting of two wheel-and-axle systems. The first is the pedal and front gear. Here, the effort force is the force that the rider exerts on the pedal, $F_{\text{rider on pedal}}$. The force of your foot is most effective when the force is exerted perpendicular to the arm of the pedal; that is, when the torque is largest. Therefore, we will assume that $F_{\text{rider on pedal}}$ is applied perpendicular to the pedal arm. The resistance is the force that the front gear exerts on the chain, $F_{\text{gear on chain}}$.

READING CHECK Identify the effort force and the resistance force for the pedal and front gear.

The rear gear and the rear wheel act like another wheel and axle. The chain exerts an effort force on the rear gear, $F_{\text{chain on gear}}$. This force is equal to the force of the front gear on the chain. That is $F_{\text{gear on chain}} = F_{\text{chain on gear}}$. The resistance force is the force that the wheel exerts on the road, $F_{\text{wheel on road}}$.

The *MA* of a compound machine is the product of the *MA*s of the simple machines from which it is made. Therefore, the bicycle's mechanical advantage is given by the following equation:

$$MA_{\text{total}} = MA_{\text{pedal gear}} \times MA_{\text{rear wheel}}$$

$$MA_{\text{total}} = \left(\frac{F_{\text{gear on chain}}}{F_{\text{rider on pedal}}}\right)\left(\frac{F_{\text{wheel on road}}}{F_{\text{chain on gear}}}\right) = \frac{F_{\text{wheel on road}}}{F_{\text{rider on pedal}}}$$

Recall that $F_{\text{gear on chain}} = F_{\text{chain on gear}}$. Therefore, they cancel in the equation shown above.

Similarly, the *IMA* of the bicycle is $IMA = IMA_{\text{pedal gear}} \times IMA_{\text{rear wheel}}$. For each wheel and axle, the IMA is the ratio of the wheel to the axle.

For the pedal gear, $IMA = \dfrac{\text{pedal radius}}{\text{front gear radius}}$

For the rear wheel, $IMA = \dfrac{\text{rear gear radius}}{\text{wheel radius}}$

For the bicycle, then,

$$IMA = \left(\frac{\text{pedal radius}}{\text{front gear radius}}\right)\left(\frac{\text{rear gear radius}}{\text{wheel radius}}\right)$$

$$= \left(\frac{\text{rear gear radius}}{\text{front gear radius}}\right)\left(\frac{\text{pedal radius}}{\text{wheel radius}}\right)$$

READING CHECK Explain What are the units of *MA* and *IMA* for the bicycle?

EXAMPLE PROBLEM 4

Find help with isolating a variable. Math Handbook

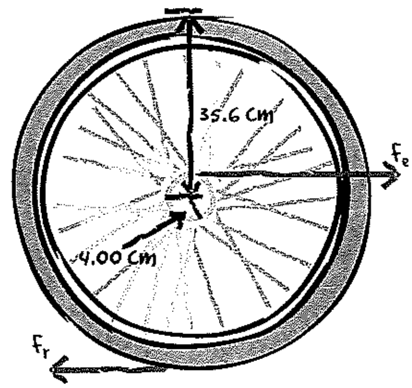
MECHANICAL ADVANTAGE You examine the rear wheel on your bicycle. It has a radius of 35.6 cm and has a gear with a radius of 4.00 cm. When the chain is pulled with a force of 155 N, the wheel rim moves 14.0 cm. The efficiency of this part of the bicycle is 95.0 percent.

a. What is the *IMA* of the wheel and gear?

b. What is the *MA* of the wheel and gear?

c. What is the resistance force?

d. How far was the chain pulled to move the rim 14.0 cm?



1 ANALYZE AND SKETCH THE PROBLEM

- Sketch the wheel and axle.
- Sketch the force vectors.

KNOWN		UNKNOWN	
$r_e = 4.00$ cm	$e = 95.0\%$	$IMA = ?$	$F_r = ?$
$r_r = 35.6$ cm	$d_r = 14.0$ cm	$MA = ?$	$d_e = ?$
$F_e = 155$ N			

2 SOLVE FOR THE UNKNOWN

a. Solve for *IMA*.

$$IMA = \frac{r_e}{r_r}$$ ◀ For a wheel-and-axle machine, *IMA* is equal to the ratio of radii.

$$= \frac{4.00\text{ cm}}{35.6\text{ cm}} = 0.112$$ ◀ Substitute $r_e = 4.00$ cm, $r_r = 35.6$ cm.

b. Solve for *MA*.

$$e = \frac{MA}{IMA} \times 100$$

$$MA = \left(\frac{e}{100}\right) \times IMA$$

$$= \left(\frac{95.0}{100}\right) \times 0.112 = 0.106$$ ◀ Substitute $e = 95.0\%$, $IMA = 0.112$.

c. Solve for force.

$$MA = \frac{F_r}{F_e}$$

$$F_r = (MA)(F_e)$$

$$= (0.106)(155\text{ N}) = 16.4\text{ N}$$ ◀ Substitute $MA = 0.106$, $F_e = 155$ N.

d. Solve for distance.

$$IMA = \frac{d_e}{d_r}$$

$$d_e = (IMA)(d_r)$$

$$= (0.112)(14.0\text{ cm}) = 1.57\text{ cm}$$ ◀ Substitute $IMA = 0.112$, $d_r = 14.0$ cm.

3 EVALUATE THE ANSWER

- **Are the units correct?** Force is measured in newtons, and distance in centimeters.
- **Is the magnitude realistic?** *IMA* is low for a bicycle because a greater F_e is traded for a greater d_r. *MA* is always smaller than *IMA*. Because *MA* is low, F_r also will be low. The small distance the axle moves results in a large distance covered by the wheel. Thus, d_e should be very small.

PRACTICE PROBLEMS

Do additional problems. Online Practice

25. If the gear radius of the bicycle in Example Problem 4 is doubled while the force exerted on the chain and the distance the wheel rim moves remain the same, what quantities change, and by how much?

26. A sledgehammer is used to drive a wedge into a log to split it. When the wedge is driven 0.20 m into the log, the log is separated a distance of 5.0 cm. A force of 1.7×10^4 N is needed to split the log, and the sledgehammer exerts a force of 1.1×10^4 N.

a. What is the *IMA* of the wedge?

b. What is the *MA* of the wedge?

c. Calculate the efficiency of the wedge as a machine.

27. A worker uses a pulley to raise a 24.0-kg carton 16.5 m, as shown in **Figure 15.** A force of 129 N is exerted, and the rope is pulled 33.0 m.

a. What is the *MA* of the pulley?

b. What is the efficiency of the pulley?

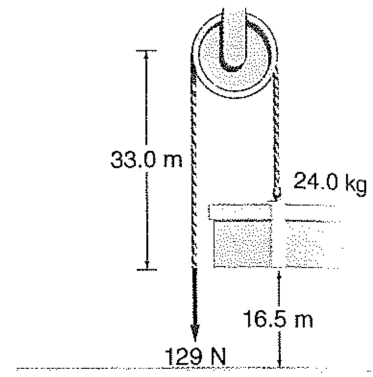


Figure 15

28. A winch has a crank with a 45-cm radius. A rope is wrapped around a drum with a 7.5-cm radius. One revolution of the crank turns the drum one revolution.

a. What is the ideal mechanical advantage of this machine?

b. If, due to friction, the machine is only 75 percent efficient, how much force would have to be exerted on the handle of the crank to exert 750 N of force on the rope?

29. CHALLENGE You exert a force of 225 N on a lever to raise a 1.25×10^3-N rock a distance of 13 cm. If the efficiency of the lever is 88.7 percent, how far did you move your end of the lever?

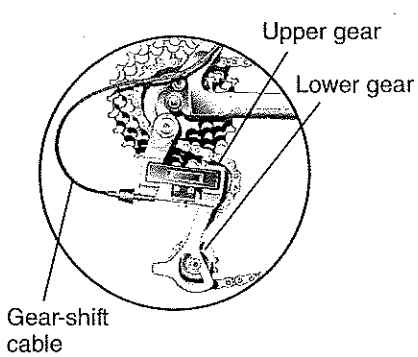
Multi-gear bicycle Shifting gears on a bicycle is a way of adjusting the ratio of gear radii to obtain the desired *IMA*. On a multi-gear bicycle, the rider can change the *IMA* of the machine by choosing the size of one or both gears. **Figure 16** shows a rear gear with five different gear sizes. When accelerating or climbing a hill, the rider increases the ideal mechanical advantage to increase the force that the wheel exerts on the road.

To increase the *IMA*, the rider needs to make the rear gear radius large compared to the front gear radius (refer to the *IMA* equation earlier in the section). For the same force exerted by the rider, a larger force is exerted by the wheel on the road. However, the rider must rotate the pedals through more turns for each revolution of the wheel.

On the other hand, less force is needed to ride the bicycle at high speed on a level road. The rider needs a small rear gear and a large front gear, resulting in a smaller *IMA*. Thus, for the same force exerted by the rider, a smaller force is exerted by the wheel on the road. However, in return, the rider does not have to move the pedals as far for each revolution of the wheel.

An automobile transmission works in the same way. To accelerate a car from rest, large forces are needed and the transmission increases the *IMA* by increasing the gear ratio. At high speeds, however, the transmission reduces the gear ratio and the *IMA* because smaller forces are needed. Even though the speedometer shows a high speed, the tachometer indicates the engine's low angular speed.

Figure 16 A rider can change the *IMA* of the bicycle by shifting gears.



☑ **READING CHECK Explain** why your car needs multiple gears.

The Human Walking Machine

CONNECTION TO BIOLOGY Movement of the human body is explained by the same principles of force and work that describe all motion. Simple machines, in the form of levers, give humans the ability to walk, run, and perform many other activities. The lever systems of the human body are complex. However, each system has the following four basic parts:

1. a rigid bar (bone)
2. a source of force (muscle contraction)
3. a fulcrum or pivot (movable joints between bones)
4. a resistance (the weight of the body or an object being lifted or moved)

Figure 17 shows these parts in the lever system in a human leg.

Lever systems of the body are not very efficient, and mechanical advantages are low. This is why walking and jogging require energy (burn calories) and help people lose weight.

When a person walks, the hip acts as a fulcrum and moves through the arc of a circle, centered on the foot. The center of mass of the body moves as a resistance around the fulcrum in the same arc. The length of the radius of the circle is the length of the lever formed by the bones of the leg. Athletes in walking races increase their velocity by swinging their hips upward to increase this radius.

A tall person's body has lever systems with less mechanical advantage than a short person's does. Although tall people usually can walk faster than short people can, a tall person must apply a greater force to move the longer lever formed by the leg bones. How would a tall person do in a walking race? What are the factors that affect a tall person's performance? Walking races are usually 20 or 50 km long. Because of the inefficiency of their lever systems and the length of a walking race, very tall people rarely have the stamina to win.

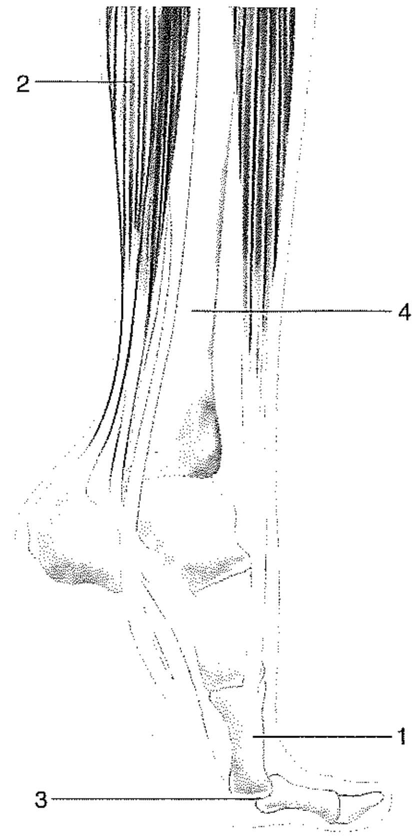


Figure 17 The human leg and foot function as a compound machine.

SECTION 2 REVIEW

Section Self-Check Check your understanding.

30. MAINIDEA Classify each tool as a lever, a wheel and axle, an inclined plane, or a wedge. Describe how it changes the force to make the task easier.

a. screwdriver
b. pliers
c. chisel
d. nail puller

31. IMA A worker is testing a multiple pulley system to estimate the heaviest object that he could lift. The largest downward force he can exert is equal to his weight, 875 N. When the worker moves the rope 1.5 m, the object moves 0.25 m. What is the heaviest object that he could lift?

32. Compound Machines A winch has a crank on a 45-cm arm that turns a drum with a 7.5-cm radius through a set of gears. It takes three revolutions of the crank to rotate the drum through one revolution. What is the *IMA* of this compound machine?

33. Efficiency Suppose you increase the efficiency of a simple machine. Do the *MA* and *IMA* increase, decrease, or remain the same?

34. Critical Thinking The mechanical advantage of a multi-gear bicycle is changed by moving the chain to a suitable rear gear.

a. To start out, you must accelerate the bicycle, so you want to have the bicycle exert the greatest possible force. Should you choose a small or large gear?

b. As you reach your traveling speed, you want to rotate the pedals as few times as possible. Should you choose a small or large gear?

c. Many bicycles also let you choose the size of the front gear. If you want even more force to accelerate while climbing a hill, would you move to a larger or smaller front gear?