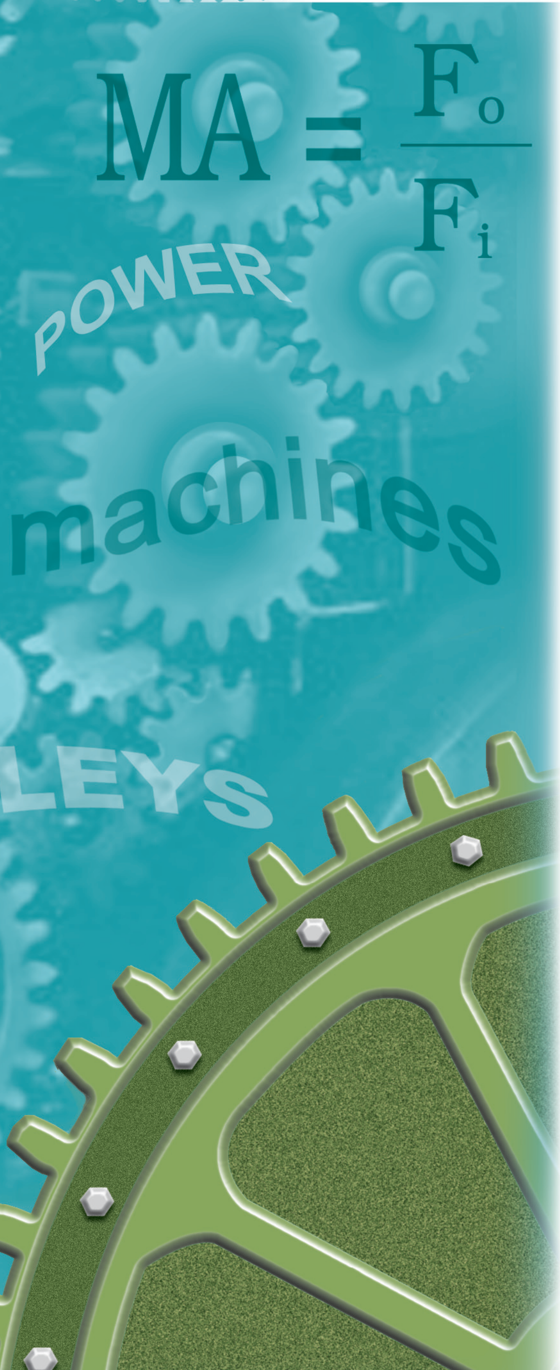
Chapter 4

Machines, Work, and Energy



The Egyptian pyramids were built about 4,000 years ago. It took workers approximately 80 years to build the pyramids at Giza. The largest, called the Great Pyramid, contains about 1 million stone blocks, each weighing about 2.5 tons. How were the ancient Egyptians able to build such an incredible monument?

What did the ancient Egyptians use to help them build the pyramids? Egyptologists, men and women that study ancient Egypt, disagree about the details of how the gigantic structures were built, but most agree that a system of ramps and levers (*simple machines*) was necessary for moving and placing the blocks. The fact that they could move such enormously massive blocks of limestone to build the Great Pyramid to a height of 481 feet (roughly equivalent to a 48-story building) is fascinating, don't you think? Perhaps the most amazing part of this story is that the Great Pyramid at Giza still stands, and is visited by tens of thousands of people each year.

Key Questions

✓ Why does stretching a rubber band increase its potential energy?

✓ How much power can a highly trained athlete have?

✓ What is one of the most perfect machines ever invented?

✓ Why does time always move forward, and never backward?

4.1 Work and Power

Energy is a measure of an object's ability to do work. Suppose you lift your book over your head. The book gets potential energy which comes from your action. Now suppose you lift your book fast, then lift it again slowly. The energy is the same because the height is the same. But it feels different to transfer the energy fast or slow. The difference between moving energy fast or slow is described by *power*. Power is the rate at which energy flows or at which work is done. This section is about power and its relation to work and energy.

Reviewing the definition of work

What "work" means in physics

In the last chapter you learned that work has a very specific meaning in physics. Work is the transfer of energy that results from applying a force over a distance. If you push a block with a force of one newton for a distance of one meter, you do one joule of work. Both work and energy are measured in the same units (joules) because work is a form of energy.

Work is done on objects

When thinking about work you should always be clear about which force is doing the work. Work is done by forces *on* objects. If you push a block one meter with a force of one newton, you have done one joule of work (Figure 4.1).

WORK

$$W = Fd$$

Work (joules) → W

Force (newtons) → F

Distance (meters) in the direction of the force → d

Energy is needed to do work

An object that has energy is able to do work; without energy, it is impossible to do work. A block that slides across a table has kinetic energy that can be used to do work. If the block hits a ball, it will do work on the ball and change its motion. Some of the block's kinetic energy is transferred to the ball. An elastic collision is a common method of doing work.

Vocabulary

power, watt, horsepower

Objectives

- ✓ Define work in terms of force and distance and in terms of energy.
- ✓ Calculate the work done when moving an object.
- ✓ Explain the relationship between work and power.

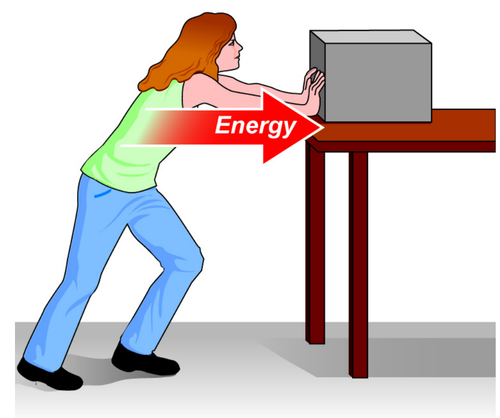


Figure 4.1: *A force of 1 newton applied for 1 meter does one joule of work on the block.*

Work and energy

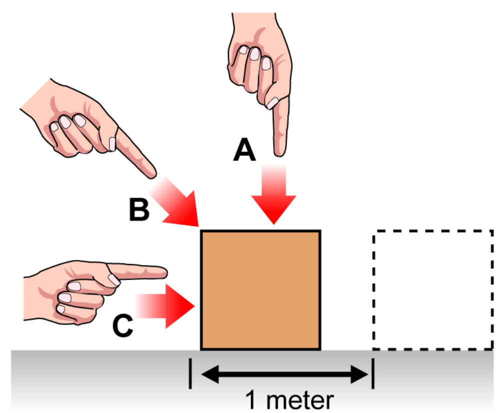
Work and potential energy Doing work always means transferring energy. The energy may be transferred to the object you apply the force to, or it may go somewhere else. You can increase the potential energy of a rubber band by exerting a force that stretches it. The work you do stretching the rubber band is stored as energy of the rubber band. The rubber band can then use the energy to do work on a paper airplane, giving it kinetic energy (Figure 4.2).

Work may not increase the energy of an object You can do work on a block by sliding it across a level table. In this example, though, the work you do does not increase the energy of the block. Because the block will not slide back all by itself, it does not gain the ability to do work *itself*, therefore gains no energy. Your work is done to overcome friction. The block does gain a tiny bit of energy because its temperature rises slightly from friction. However, that energy comes from the force of friction, not from your applied force.

Not all force does work Sometimes force is applied to an object, but no work is done. If you push down on a block sitting on a table and it doesn't move, you have not done any work on the block (force A below). If you use $W=Fd$ to calculate the work, you will get zero no matter how strong the force because the distance is zero.

Force at an angle to distance There are times when only *some* of a force does work. Force B is applied at an angle to the direction of motion of a block. Only a portion of the force is in the direction the block moves, so only that portion of the force does work.

Doing the most work The more exact calculation of work is the product of the portions of force and distance that are *in the same direction*. To do the greatest amount of work, you must apply force in the direction the object will move (force C). If forces A, B, and C have equal strengths, force C will do the most work because it is entirely in the direction of the motion.



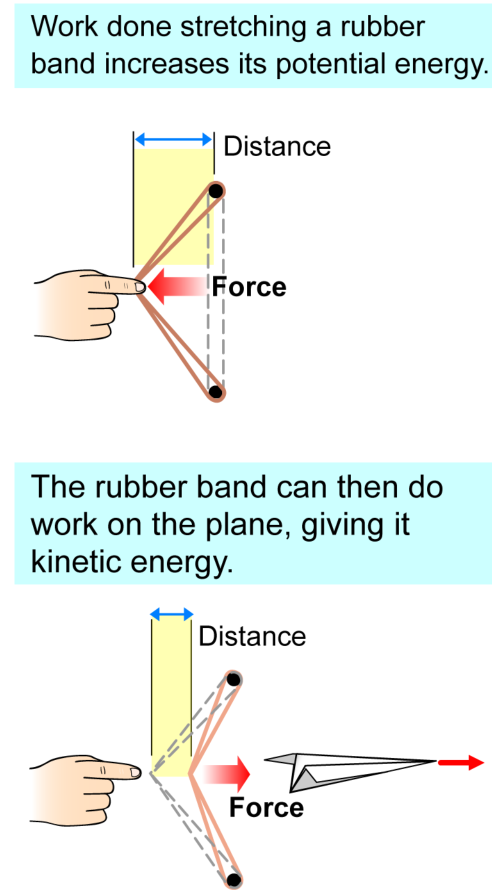


Figure 4.2: *You can do work to increase an object's potential energy. Then the potential energy can be converted to kinetic energy.*

Work done against gravity

Lifting force equals the weight

Many situations involve work done by or against the force of gravity. To lift something off the floor, you must apply an upward force with a strength equal to the object's weight. The work done while lifting an object is equal to its change in potential energy. It does not matter whether you lift the object straight up or you carry it up the stairs in a zigzag pattern. The work is the same in either case. Work done against gravity is calculated by multiplying the object's weight by its change in height.

Why the path does not matter

The reason the path does not matter is found in the definition of work as the force times the distance moved *in the direction of the force*. If you move an object on a diagonal, only the vertical distance matters because the force of gravity is vertical (Figure 4.3). It is much easier to climb stairs or go up a ramp but the work done *against gravity* is the same as if you jumped straight up. Stairs and ramps are easier because you need less force. But you have to apply the force over a longer distance. In the end, the total work done against gravity is the same no matter what path you take.

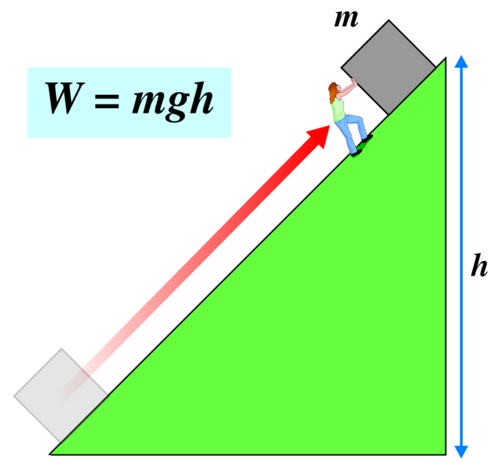


Figure 4.3: *The work done when lifting an object equals its mass multiplied by the strength of gravity multiplied by the change in height.*

Calculating work

Alexander has a mass of 70 kilograms. His apartment is on the second floor, 5 meters up from ground level. How much work does he do against gravity each time he climbs the stairs to his apartment?

1. Looking for: You are asked for the work.

2. Given: You are given the mass in kilograms and the height in meters.

3. Relationships: $F_g = mg \qquad W = Fd$

4. Solution: The force is equal to Alexander's weight.
$F_g = (70\text{ kg})(9.8\text{ m/sec}^2) \quad F_g = 686\text{ N}$

Use the force to calculate the work.
$W = (686\text{ N})(5\text{ m}) \quad W = 3430\text{ J}$ He does 3430 joules of work.

Your turn...

a. How much additional work does Alexander have to do if he is carrying 5 kilograms of groceries? **Answer:** 245 J

b. A car engine does 50,000 J of work to accelerate at 10 m/sec^2 for 5 meters. What is the mass of the car? **Answer:** 1,000 kg

Power

What is power? Suppose Michael and Jim each lift a barbell weighing 100 newtons from the ground to a height of two meters (Figure 4.4). Michael lifts quickly and Jim lifts slowly. Because the barbell is raised the same distance, it gains the same amount of potential energy in each case. Michael and Jim do the same amount of work. However, Michael's *power* is greater because he gets the work done in less time. **Power** is the rate at which work is done.

Units of power The unit for power is equal to the unit of work (joules) divided by the unit of time (seconds). One **watt** is equal to one joule per second. The watt was named after James Watt (1736-1819), the Scottish engineer who invented the steam engine. Another unit of power that is often used for engine power is the **horsepower**. Watt expressed the power of his engines as the number of horses an engine could replace. One horsepower is equal to 746 watts.

POWER

Power (watts) → $$P = \frac{W}{t}$$ ← *Work* (joules) ← *Time* (seconds)

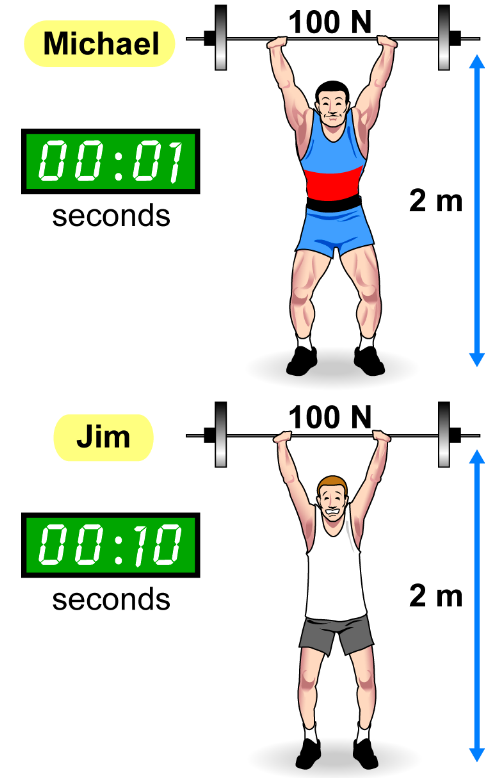


Figure 4.4: *Michael and Jim do the same amount of work but do not have the same power.*

Calculating work So how much power do Michael and Jim use? You must first calculate the work they do, using $W = Fd$. The force needed to lift the barbell is equal to its weight (100 N). The work is therefore 100 newtons times two meters, or 200 joules. Each of them does 200 joules of work.

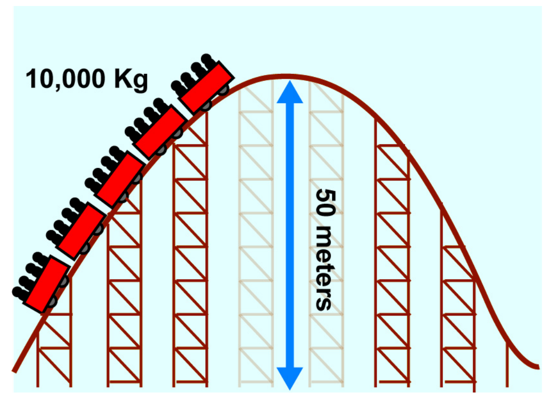
Calculating power To find Michael's power, divide his work (200 joules) by his time (1 second). Michael has a power of 200 watts. To find Jim's power, divide his work (200 joules) by his time (10 seconds). Jim's power is 20 watts. Jim takes 10 times as long to lift the barbell, so his power is one-tenth as great.

Calculating power

Human power The maximum power output of a person is typically around a few hundred watts. However, it is only possible to keep up this power for a short time. Highly trained athletes can keep up a power of 350 watts for about an hour. An average person running or biking for a full hour produces an average power of around 200 watts.

Calculating power

A roller coaster is pulled up a hill by a chain attached to a motor. The roller coaster has a total mass of 10,000 kg. If it takes 20 seconds to pull the roller coaster up a 50-meter hill, how powerful is the motor?



1. Looking for: You are asked for power.

2. Given: You are given the mass in kilograms, the time in seconds, and the height in meters.

3. Relationships: $F_g = mg$ $W = Fd$ $P = W/t$

4. Solution: Calculate the weight of the roller coaster:
$F_g = (10{,}000 \text{ kg})(9.8 \text{ m/sec}^2)$ $F_g = 98{,}000 \text{ N}$
Calculate the work:
$W = (98{,}000 \text{ N})(50 \text{ m})$ $W = 4{,}900{,}000 \text{ J or } 4.9 \times 10^6 \text{ J}$
Calculate the power:
$P = (4.9 \times 10^6 \text{ J}) \div (20 \text{ sec})$ $P = 245{,}000 \text{ watts}$

Your turn...

a. What would the motor's power be if it took 40 seconds to pull the same roller coaster up the hill? **Answer:** 122,500 watts
b. What is the power of a 70-kilogram person who climbs a 10-meter-high hill in 45 seconds? **Answer:** 152 watts

4.1 Section Review

1. Explain how work is related to energy.
2. Who does more work, a person who lifts a 2-kilogram object 5 meters or a person who lifts a 3-kilogram object 4 meters?
3. While sitting in class, your body exerts a force of 600 N on your chair. How much work do you do?
4. Is your power greater when you run or walk up a flight of stairs? Why?

4.2 Simple machines

How do you move something that is too heavy to carry? How did the ancient Egyptians build the pyramids long before the invention of powered machines? The answer to these questions has to do with the use of simple machines. In this section, you will learn how simple machines multiply forces to accomplish many tasks.

Vocabulary

machine, input, output, fulcrum, simple machines, mechanical advantage, fulcrum, input arm, output arm, tension

Objectives

- ✓ Describe how a machine works in terms of input and output.
- ✓ Define simple machines and name some examples.
- ✓ Calculate the mechanical advantage of a simple machine given the input and output force.

Using machines

What technology allows us to do

Today's technology allows us to do incredible things. Moving huge steel beams, digging tunnels that connect two islands, and building 1,000-foot skyscrapers are examples. What makes these accomplishments possible? Have we developed super powers since the days of our ancestors?

What is a machine?

In a way we *have* developed super powers. Our powers come from the clever human invention of machines. A **machine** is a device with moving parts that work together to accomplish a task. A bicycle is made of a combination of machines that work together. All the parts of a bicycle work as a system to transform forces from your muscles into motion. A bicycle allows you to travel at faster speeds and for greater distances than possible on foot.

The concepts of input and output

Machines are designed to do something. To understand how machines work it is useful to define an **input** and an **output**. The *input* includes everything you do to make the machine work, like pushing on the bicycle pedals, for instance. The *output* is what the machine does for you, like going fast or climbing a steep hill. For the machines that are the subject of this chapter, the input and output may be force, power, or energy.

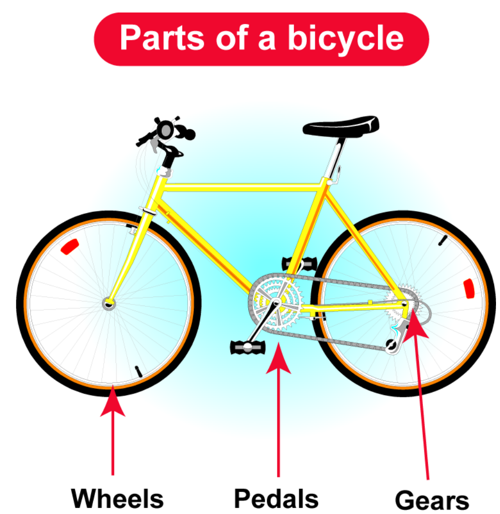
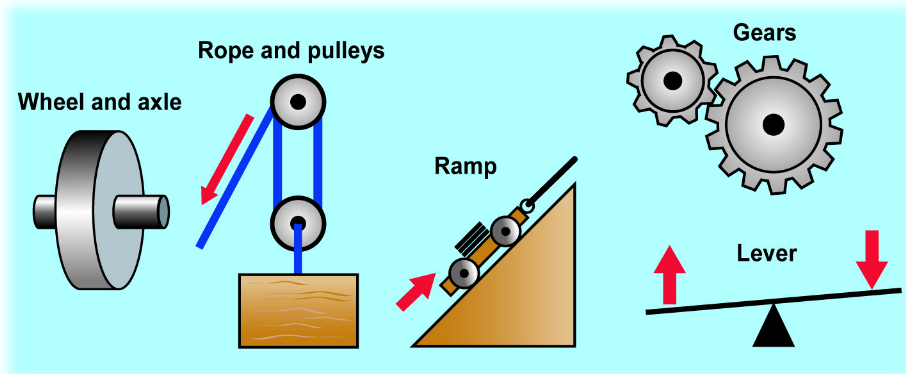


Figure 4.5: *A bicycle contains machines working together.*

Simple machines

The beginning of technology The development of the technology that created cars, airplanes, and other modern conveniences began with the invention of **simple machines**. A simple machine is an unpowered mechanical device that accomplishes a task with only one movement (such as a lever). A lever allows you to move a rock that weighs 10 times (or more) what you weigh. Some important types of simple machines are shown below.



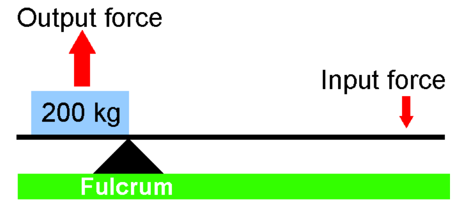


Figure 4.6: *A small input force can create a large output force if the lever is arranged correctly.*

Input force and output force Simple machines work with forces. The *input force* is the force you apply to the machine. The *output force* is the force the machine applies to what you are trying to move. Figure 4.6 shows how a lever can be arranged to create a large output force from a small input force.

Ropes and pulleys A rope and pulley system is a simple machine made by connecting a rope to one or more pulleys. You apply the input force to the rope and the output force is exerted on the load you are lifting. One person could easily lift an elephant with a properly designed system of pulleys (Figure 4.7).

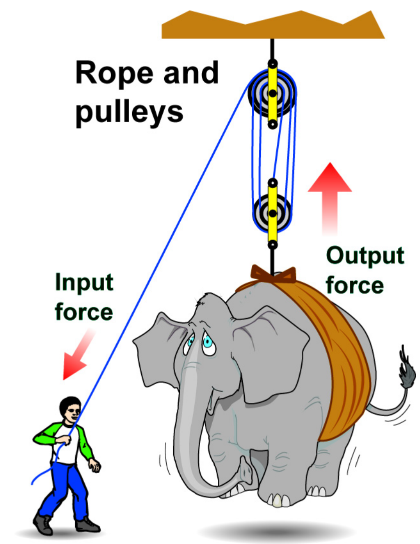


Figure 4.7: *A simple machine made with a rope and pulley allows one person to lift tremendous loads.*

Machines within machines Most of the machines we use today are made up of combinations of different types of simple machines. For example, the bicycle uses wheels and axles, levers (the pedals and kickstand), and gears. If you take apart a complex machine such as a video cassette recorder, a clock, or a car engine, you will find many simple machines inside. In fact, a VCR contains simple machines of every type including screws, ramps, pulleys, wheels, gears, and levers.

Mechanical advantage

Ratio of output to input force

Simple machines are best understood through the concepts of input and output forces. The **mechanical advantage** of a machine is the ratio of the output force to the input force. If the mechanical advantage of a machine is larger than one, the output force is larger than the input force. A mechanical advantage smaller than one means the output force is smaller than the input force. Mechanical advantage is a ratio of forces, so it is a pure number without any units.

MECHANICAL ADVANTAGE

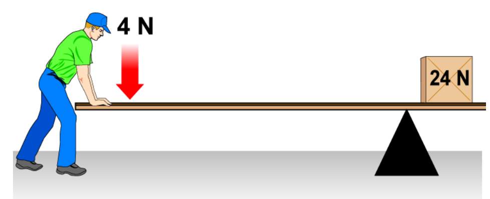
Mechanical advantage → $$MA = \frac{F_o}{F_i}$$

Output force (N)

Input force (N)

Calculating mechanical advantage

What is the mechanical advantage of a lever that allows Jorge to lift a 24-newton box with a force of 4 newtons?



1. Looking for: You are asked for the mechanical advantage.

2. Given: You are given the input force and the output force in newtons.

3. Relationships: $MA = F_o/F_i$

4. Solution: $MA = (24\text{ N})/(4\text{ N})$
$MA = 6$

a. Calculate the mechanical advantage of a rope and pulley system that requires 10 newtons of force to lift a 200-newton load.
Answer: 20

b. You use a block and tackle with a mechanical advantage of 30. How heavy a load can you lift with an input force of 100 N?
Answer: 3000 N

Work and machines

Input and output work

A simple machine does work because it exerts forces over a distance. If you are using the machine you also do work, because you apply forces to the machine that move its parts. By definition, a simple machine has no source of energy except the immediate forces you apply. That means the only way to get output work *from* a simple machine is to do input work *on* the machine. In fact, the output work done by a simple machine can never exceed the input work done on the machine. This is an important result.

Perfect machines

In a *perfect* machine the output work equals the input work. Of course, there are no perfect machines. Friction always converts some of the input work to heat and wear, so the output work is always *less* than the input work. However, for a well-designed machine, friction can be small and we can often assume input and output work are approximately equal.

An example

Figure 4.8 shows a simple machine that has a mechanical advantage of two. The machine lifts a 10-newton weight a distance of one-half meter. The output work is five joules (10 N × 0.5 m).

You must do at least five joules of work on the machine to lift the weight. If you assume the machine is perfect, then you must do exactly 5 J of input work to get 5 J of output work. The input force is only five newtons since the machine has a mechanical advantage of two. That means the input distance must be 1 meter because 5 N × 1 m = 5 J. You have to pull one meter of rope to raise the weight one-half meter.

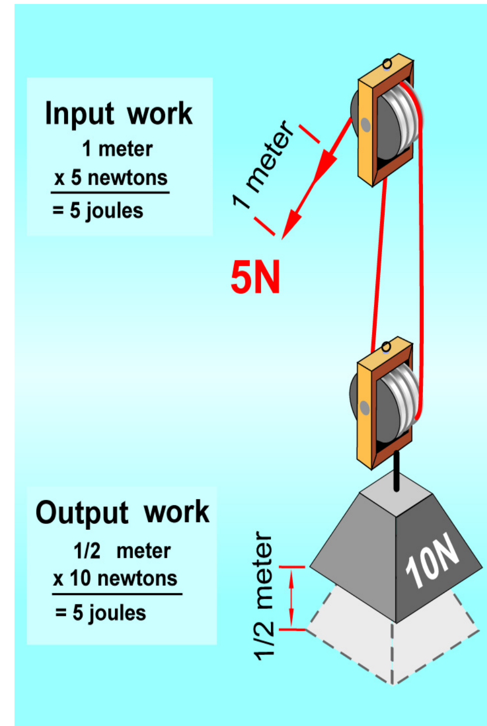


Figure 4.8: *The work output equals the work input even though the forces differ.*

The cost of multiplying force

The output work of a machine can never be greater than the input work. This is a rule that is *true for all machines*. Nature does not give something for nothing. When you design a machine that multiplies force, you pay by having to apply the force over a greater distance.

The force and distance are related by the amount of work done. In a perfect (theoretical) machine, the output work is exactly equal to the input work. If the machine has a mechanical advantage greater than one, the input force is less than the output force. However, the input force must be applied over a longer distance to satisfy the rule about input and output work.

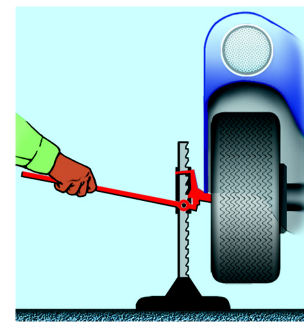
Using work to solve problems

Mechanical advantage To solve mechanical advantage problems, start by assuming a perfect machine, with nothing lost to friction. Set the input and output work equal and use this relationship to find the mechanical advantage.

Force or distance Many problems give three of the four quantities: input force, input distance, output force, and output distance. If the input and output work are equal then force × distance at the input of the machine equals force × distance at the output. Using this equation, you can solve for the unknown force or distance.

Work and machines

A jack is used to lift one side of a car in order to replace a tire. To lift the car, the jack handle moves 30 centimeters for every one centimeter that the car is lifted. If a force of 150 newtons is applied to the jack handle, what force is applied to the car by the jack? You can assume all of the input work equals output work.



1. Looking for: You are asked for the output force in newtons.

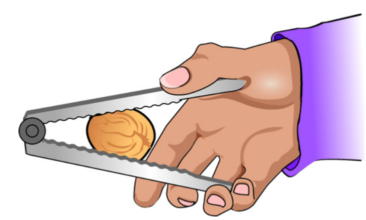
2. Given: You are given the input force in newtons, and the input distance and output distance in centimeters. Convert these distances to meters.

3. Relationships: $Work = Force \times distance$ and Input work = output work

4. Solution: Input work: $W = (150\text{ N})(0.30\text{ m}) = 45$ joules
Output work: 45 J of input work = $Force \times 0.01$ m
$F = 45\text{ J}/ 0.01\text{ m} = 4{,}500$ newtons
The jack exerts an upward force of 4,500 newtons on the car.

Your turn...

a. A mover uses a pulley to lift a 2,400-newton piano up to the second floor. Each time he pulls the rope down 2 meters (input distance), the piano moves up 0.25 meter (output distance). With what force does the mover pull on the rope? **Answer:** 300 newtons



b. A nutcracker is a very useful lever. The center of the nutcracker (where the nut is) moves one centimeter for each two centimeters your hand squeezes down. If a force of 40 newtons is needed to crack the shell of a walnut, what force must you apply? **Answer:** 20 newtons

How a lever works

Example of a lever A lever can be made by balancing a board on a log (Figure 4.9). Pushing down on one end of the board lifts a load on the other end of the board. The downward force you apply is the input force. The upward force the board exerts on the load is the output force.

Parts of the lever All levers include a stiff structure that rotates around a fixed point called the **fulcrum**. The side of the lever where the input force is applied is called the **input arm**. The **output arm** is the end of the lever that applies the output force. Levers are useful because you can arrange the fulcrum and the input and output arms to make almost any mechanical advantage you need.

Changing direction When the fulcrum is in the middle of the lever, the input and output forces are the same. An input force of 100 newtons makes an output force of 100 newtons. The input and output forces are different if the fulcrum is not in the center of the lever (Figure 4.10). The side of the lever with the longer arm has the smaller force. If the input arm is 10 times longer than the output arm, the output force is 10 times greater than the input force.

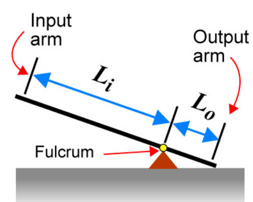
Mechanical advantage of a lever You can find the mechanical advantage of a lever by looking at two triangles. The output work is the output force multiplied by the output distance. The input work is the input distance multiplied by the input force. By setting the input and output work equal, you see that the ratio of forces is the inverse of the ratio of distances. The larger (input) distance has the smaller force. The ratio of distances is equal to the ratio of the lengths of the two arms of the lever. Using the lengths of the arms is the easiest way to calculate the mechanical advantage of a lever (below).

MECHANICAL ADVANTAGE OF A LEVER

Mechanical advantage → $$MA_{lever} = \frac{L_i}{L_o}$$

L_i — *Length of input arm* (m)

L_o — *Length of output arm* (m)



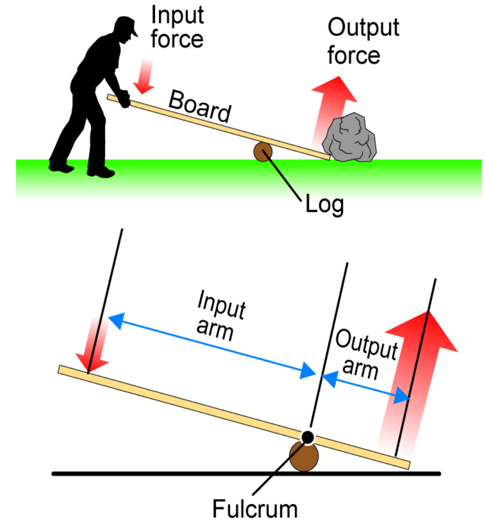


Figure 4.9: *A board and log can make a lever used to lift a rock.*

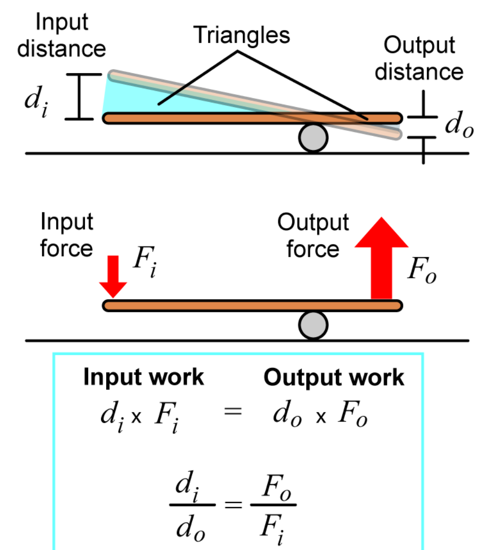


Figure 4.10: *How to determine the mechanical advantage of a lever.*

Types of levers

The output force can be *less* than the input force

You can also make a lever in which the output force is less than the input force. The input arm is shorter than the output arm on this kind of lever. You might design a lever this way if you need the motion on the output side to be larger than the motion on the input side. A very small downward motion on the input side can cause the load to lift a large distance on the output side.

The three types of levers

Levers are used in many common machines, including, for example, pliers, a wheelbarrow, and the human biceps and forearm (Figure 4.11). You may have heard the human body described as a machine. In fact, it is a machine. Bones and muscles work as levers when you do something as simple as biting an apple. Levers are classified as one of three types or classes defined by the location of the input and output forces relative to the fulcrum. The mechanical advantage is always the ratio of lengths of the input arm to the output arm.

Mechanical advantage of levers

A lever has a mechanical advantage of 4. Its input arm is 60 centimeters long. How long is its output arm?

1. Looking for: You are asked for the output arm in centimeters.

2. Given: You are given the mechanical advantage and the length of the input arm in centimeters.

3. Relationships:

$$MA_{lever} = \frac{L_i}{L_o}$$

4. Solution:

$$4 = \frac{60\text{ cm}}{L_o} \qquad 4L_o = 60\text{ cm}$$

$$L_o = \frac{60\text{ cm}}{4} = 15\text{ cm}$$

a. What is the mechanical advantage of a lever with an input arm of 25 centimeters and an output arm of 100 centimeters? **Answer:** 0.25

b. A lever has an input arm of 100 centimeters and an output arm of 10 centimeters. What is the mechanical advantage of this lever? Given this mechanical advantage, how much input force is needed to lift a 100-newton load? **Answer:** MA_{lever} = 10; 10 newtons of force would be needed.

The Three Classes of Levers

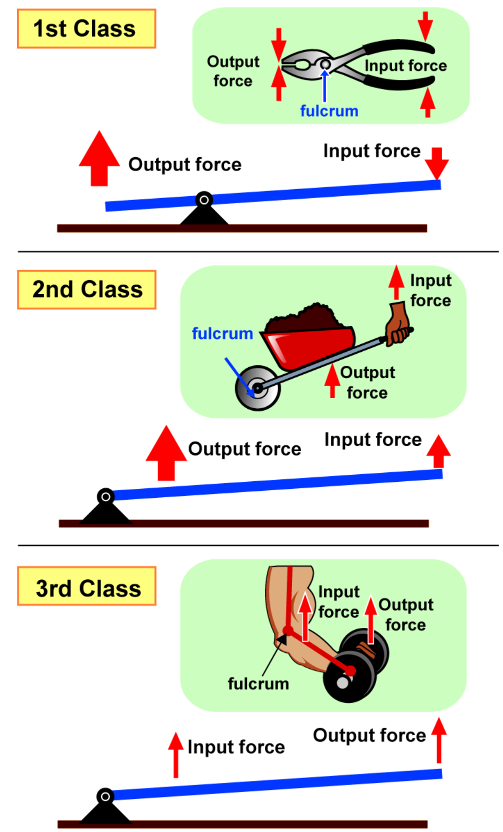
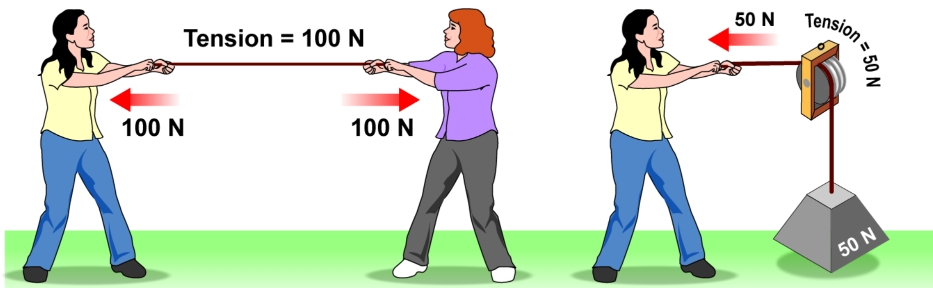


Figure 4.11: *There are three classes of levers.*

How a rope and pulley system works

Tension in ropes and strings Ropes and strings carry forces along their length. The force in a rope is called **tension** and is a pulling force that acts along the direction of the rope. The tension is the same at every point in a rope. If the rope is not moving, its tension is equal to the force pulling on each end (below). Ropes or strings do *not* carry pushing forces. This is obvious if you ever tried pushing a rope.



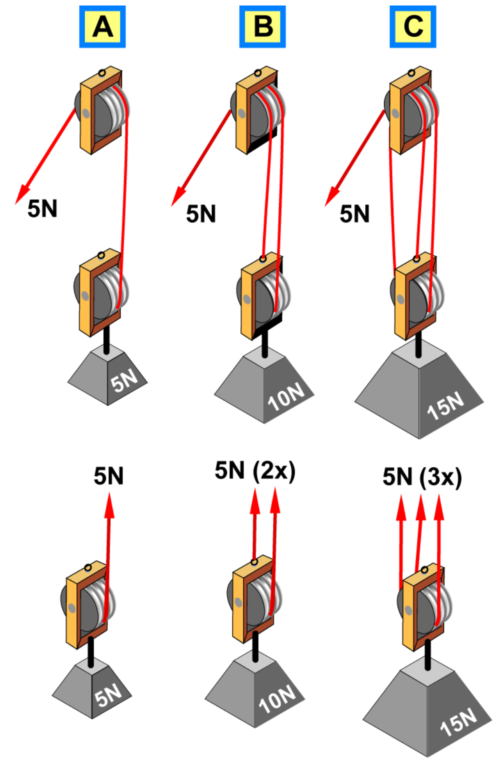
Each person pulls with a force of 100 newtons, so the tension is 100 newtons

The person and the weight each pull with 50 newtons, so the tension is 50 newtons

The forces in a pulley system Figure 4.12 shows three different configurations of ropes and pulleys. Imagine pulling with an input force of 5 newtons. In case A, the load feels a force equal to your input force. In case B, there are two strands of rope supporting the load, so the load feels twice your input force. In case C, there are three strands so the output force is three times the input force.

Mechanical advantage The mechanical advantage of a pulley system depends on the number of strands of rope directly supporting the load. In case C, three strands directly support the load, so the output force is three times the input force. The mechanical advantage is 3. To make a rope and pulley system with a greater mechanical advantage, you can increase the number of strands directly supporting the load by taking more turns around the pulleys.

Work To raise the load 1 meter in case C, the input end of the rope must be pulled for 3 meters. This is because *each* of the three supporting strands must shorten by 1 meter. The mechanical advantage is 3 but the input force must be applied for three times the distance as the output force. This is another example of the rule stating that output and input work are equal for a perfect machine.



	A	B	C
Input force	5N	5N	5N
Output force	5N	10N	15N
Mechanical advantage	1	2	3

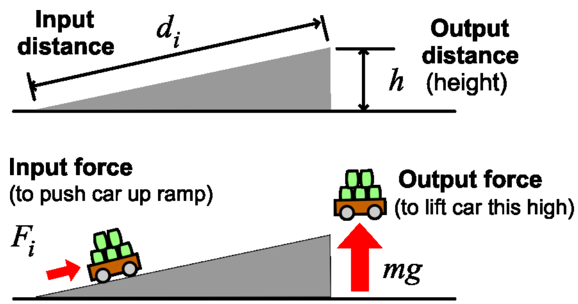
Figure 4.12: *A rope and pulley system can be arranged to have different mechanical advantages.*

Gears and ramps

Rotating motion Many machines require that rotating motion be transmitted from one place to another. The transmission of rotating motion is often done with gears (Figure 4.13). Some machines that use gears, such as small drills, require small forces at high speeds. Other machines, such as the paddle wheel on the back of a steamboat, require large forces at low speed.

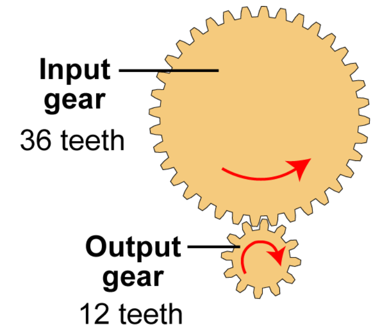
How gears work The rule for how two gears turn depends on the number of teeth on each gear. The teeth don't slip, so moving 36 teeth on one gear means that 36 teeth have to move on any connected gear. Suppose a large gear with 36 teeth is connected to a small gear with 12 teeth. As the large gear turns once around, it moves 36 teeth on the smaller gear. The smaller gear must turn three times ($3 \times 12 = 36$) for every single turn of the large gear (Figure 4.13).

Ramps A ramp is another type of simple machine. Using a ramp allows you to push a heavy car to a higher location with less force than is needed to lift the car straight up. Ramps reduce the input force needed by increasing the distance over which the input force acts. For example, suppose a 10-meter ramp is used to lift a car one meter. The output work is work done against gravity. If the weight of the car is 500 newtons, then the output work is 500 joules ($w = mgh = 500\text{ N} \times 1\text{ m}$).



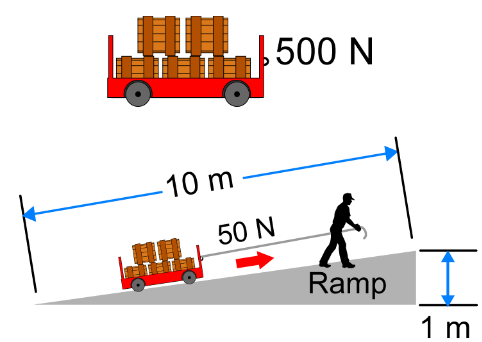
Input work		Output work
$d_i \times F_i$	=	mgh
F_i	=	$\dfrac{mgh}{d_i}$

Mechanical advantage of a ramp The input work is the input force multiplied by the length of the ramp (10 meters). If you set the input work equal to the output work, you quickly find that the input force is 50 newtons ($Fd = F \times 10\text{ m} = 500\text{ J}$). The input force is one-tenth of the output force. For a frictionless ramp, the mechanical advantage is the length of the ramp divided by the height (Figure 4.14).



$$\textbf{Gear ratio} = \frac{\text{output}}{\text{input}}$$

Figure 4.13: *The smaller gear makes three turns for each one turn of the larger gear.*



$$\textbf{Mechanical advantage} = \frac{\text{ramp length}}{\text{height}} = \frac{10}{1}$$

Figure 4.14: *The car must be pulled 10 meters to lift it up one meter, but only one-tenth the force is needed*

Screws

Screws A screw is a simple machine that turns rotating motion into linear motion (Figure 4.15). A screw works just like a ramp that curves as it gets higher. The “ramp” on a screw is called a thread. Imagine unwrapping one turn of a thread to make a straight ramp. Each turn of the screw advances the nut the same distance it would have gone sliding up the ramp. The *lead* of a screw is the distance it advances in one turn. A screw with a lead of one millimeter advances one millimeter for each turn.

A screw and screwdriver The combination of a screw and screwdriver has a very large mechanical advantage. The mechanical advantage of a screw is found by thinking about it as a ramp. The vertical distance is the lead of the screw. The length of the ramp is measured as the average circumference of the thread. A quarter-inch screw in a hardware store has a lead of 1.2 millimeters and a circumference of 17 millimeters along the thread. The mechanical advantage is 14. If you use a typical screwdriver with a mechanical advantage of 4, the total mechanical advantage is 14 × 4 or 56 (theoretically). Friction between the screw and the mating surface causes the actual mechanical advantage to be somewhat less than the theoretical value, but still very large (Figure 4.16).

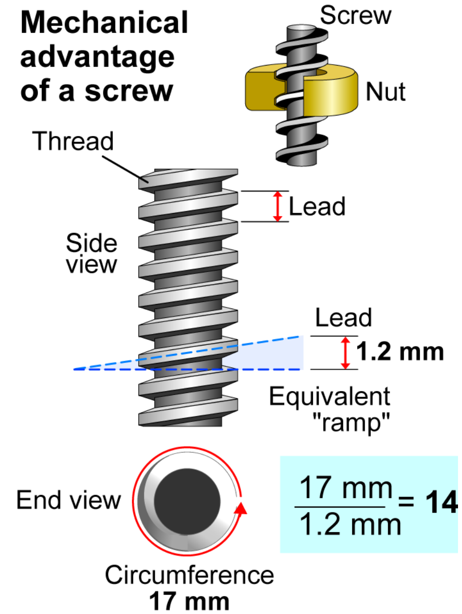
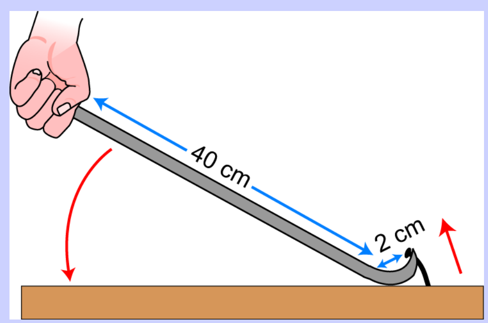


Figure 4.15: *A screw is a rotating ramp.*

4.2 Section Review

1. Name two simple machines that are found on a bicycle.
2. Calculate the mechanical advantage of the crowbar shown at right.
3. Classify each of these as a first-, second-, or third-class levers: see-saw, baseball bat, door on hinges, scissors (Figure 4.16).
4. A large gear with 48 teeth is connected to a small gear with 12 teeth. If the large gear turns twice, how many times must the small gear turn?
5. What is the mechanical advantage of a 15 meter ramp that rises 3 meters?



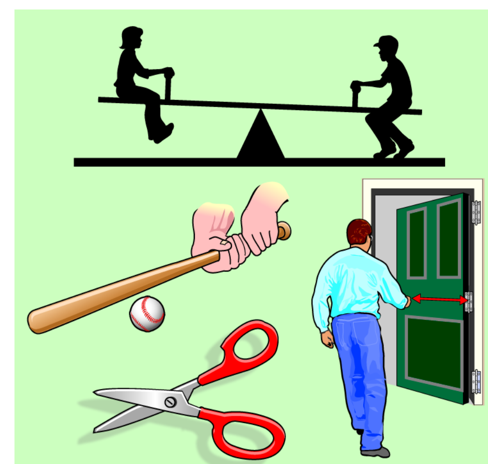


Figure 4.16: *Which type of lever is shown in each picture?*

4.3 Efficiency

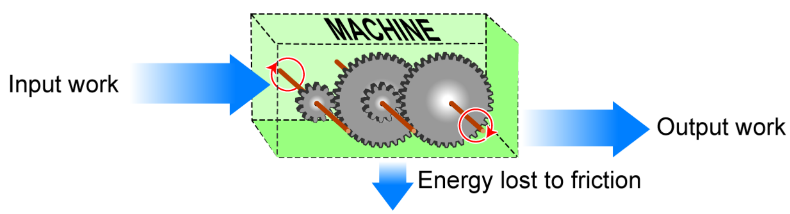
So far we have talked about perfect machines. In a perfect machine there is no friction and the output work equals the input work. Of course, there are no perfect machines in human technology. This section is about *efficiency,* which is how we measure how close to perfect a machine is. The bicycle comes as close to perfect as any machine ever invented. Up to 95 percent of the work done by the rider on the pedals becomes kinetic energy of the bicycle (Figure 4.17). Most machines are much less perfect. An automobile engine converts less than 15 percent of the chemical energy in gasoline into output work to move a car.

Friction

Friction Friction is a catch-all term for many processes that oppose motion. Friction can be caused by rubbing or sliding surfaces. Friction can also be caused by moving through liquid, such as oil or water. Friction can even be caused by moving though air, as you can easily feel by sticking your hand out the window of a moving car.

Friction and energy Friction converts energy of motion to heat and wear. The brakes on a car use friction to slow the car down and they get hot. Over time, the material of the brakes wears away. This also takes energy because the bonds between atoms are being broken as material is being worn down. When we loosely say that energy is "lost" to friction, the statement is not accurate. The energy is not lost, but converted to other forms of energy that are difficult to recover and reuse.

Machines In an actual machine, the output work is less than the input work because of friction. When analyzing a machine it helps to think like the diagram below. The input work is divided between output work and "losses" due to friction.



Vocabulary

efficiency, reversible, irreversible

Objectives

- ✓ Describe the relationship between work and energy in a simple machine.
- ✓ Use energy conservation to calculate input or output force or distance.
- ✓ Explain why a machine's input and output work can differ.

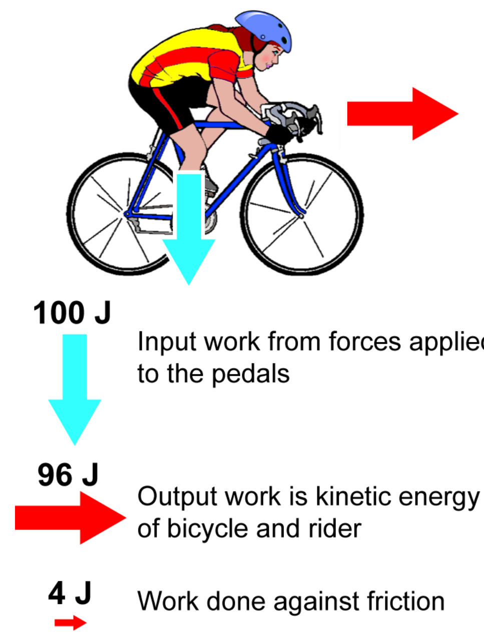


Figure 4.17: *A bicycle is highly efficient.*

Efficiency

100 percent efficient

A machine has an **efficiency** of 100 percent if the work output of the machine is equal to the work input. If a machine is 100 percent efficient, no energy is diverted by friction or other factors. Although it is impossible to create a machine with 100 percent efficiency, people who design machines try to achieve as high an efficiency as possible.

The definition of efficiency

The efficiency of a machine is the ratio of work output to work input. Efficiency is usually expressed in percent. A machine that is 75 percent efficient can produce three joules of output work for every four joules of input work (Figure 4.18). One joule out of every four (25 percent) is lost to friction. You calculate efficiency by dividing the work output by the work input. You can convert the ratio into a percent by multiplying by 100.

Improving efficiency

An important way to increase the efficiency of a machine is to reduce friction. Ball bearings and oil reduce rolling friction. Slippery materials such as Teflon™ reduce sliding friction. Designing a car with a streamlined shape reduces air friction. All these techniques increase efficiency.

A machine with 75% efficiency

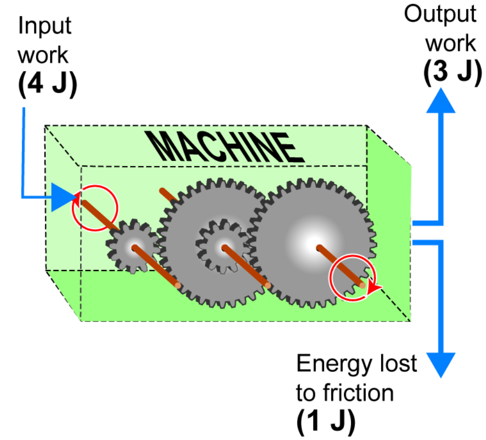


Figure 4.18: *If the input work is four joules, and the output work is three joules, then the efficiency is 75 percent.*

Calculating efficiency

A person uses a 75-newton force to push a 51-kilogram car up a ramp. The ramp is 10 meters long and rises one meter. Calculate the efficiency.

1. Looking for: You are asked for the efficiency.

2. Given: You are given the input force and distance, and the mass and height for the output.

3. Relationships: Efficiency = Output work / Input work. Input: $W = FD$. Output: work done against gravity ($W = mgh$)

4. Solution: Output work = (51 kg)(9.8 N/kg)(1 m) = 500 joules
Input work = (75 N)(10 m) = 750 joules
Efficiency = 500 J ÷ 750 J = 67%

Your turn...

a. If a machine is 80 percent efficient, how much input work is required to do 100 joules of output work?. **Answer:** 125 J

b. A solar cell needs 750 J of input energy to produce 100 J of output. What is its efficiency? **Answer:** 13.3%

Efficiency and time

A connection The efficiency is less than 100 percent for virtually all processes that convert energy to any other form except heat. Scientists believe this is connected to why time flows forward and not backward. Think of time as an arrow pointing from the past into the future. All processes move in the direction of the arrow, never backward (Figure 4.19).

Reversible processes Suppose a process were 100 percent efficient. As an example, think about connecting two marbles of equal mass by a string passing over an ideal pulley with no mass and no friction (Figure 4.20). One marble can go down, transferring its potential energy to the other marble, which goes up. The motion of the marble is **reversible** because it can go forward and backward as many times as you want. In fact, if you watched a movie of the marbles moving, you could not tell if the movie were playing forward or backward.

Friction and the arrow of time Now suppose there is a tiny amount of friction so the efficiency is 99 percent. Because some potential energy is lost to friction, every time the marbles exchange energy, some is lost and the marbles don't rise quite as high as they did the last time. If you made a movie of the motion, you could tell whether the movie was running forward or backward. Any process with an efficiency less than 100 percent runs only one way, *forward with the arrow of time*.

Irreversible processes Friction turns energy of motion into heat. Once energy is transformed into heat, the energy cannot ever completely get back into its original form. Because heat energy cannot get back to potential or kinetic energy, any process with less than 100% efficiency is **irreversible**. Irreversible processes can only go forward in time. Since processes in the universe almost always lose a little energy to friction, time cannot run backward.

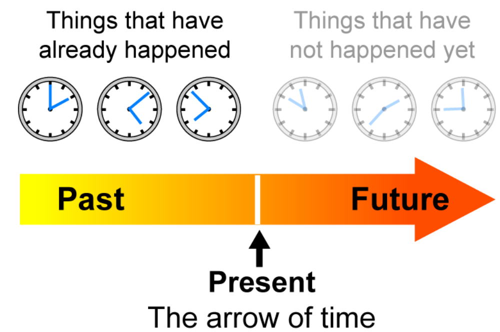


Figure 4.19: *Time can be thought of as an arrow pointing from the past into the future.*

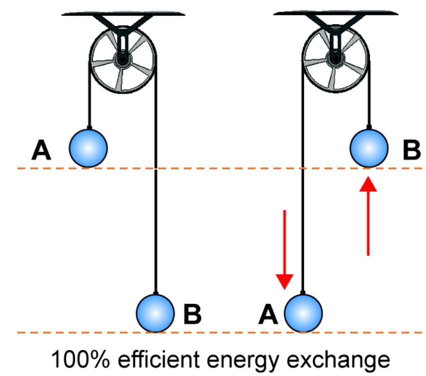


Figure 4.20: *Exchanging energy with a perfect, frictionless, massless pulley.*

4.3 Section Review

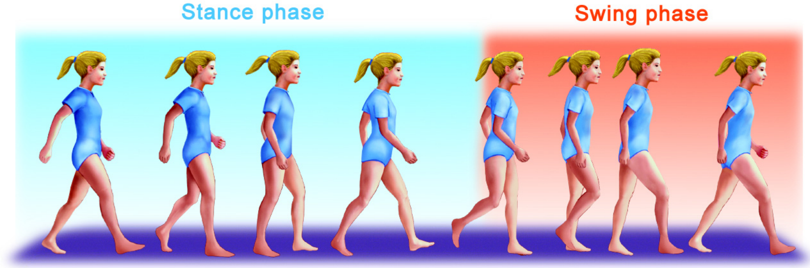
1. What is the relationship between work and energy in a machine?
2. Why can the output work of a simple machine never be greater than the input work?
3. Use the concept of work to explain the relationship between input and output forces and distances.
4. How does the efficiency of a car compare to the efficiency of a bicycle? Why do you think there is such a large difference?

Prosthetic Legs and Technology

The human leg is a complex and versatile machine. Designing a *prosthetic* (artificial) device to match the leg's capabilities is a serious challenge. Teams of scientists, engineers, and designers around the world use different approaches and technologies to develop prosthetic legs that help the user regain a normal, active lifestyle.

Studying the human gait cycle

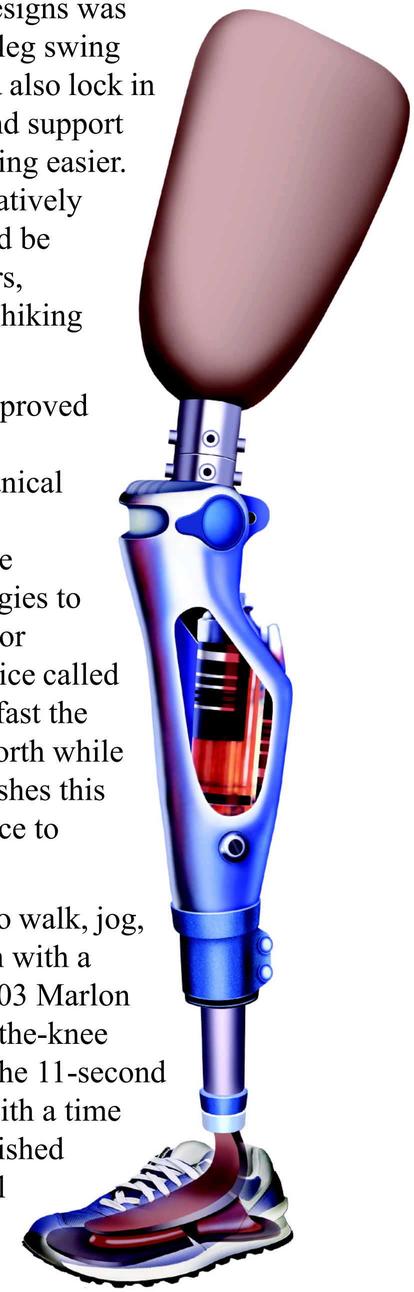
Each person has a unique way of walking. But studying the way humans walk has revealed that some basic mechanics hold true for just about everyone. Scientists analyze how we walk by looking at our "gait cycle." The gait cycle consists of two consecutive strides while walking, one foot and then the other. By breaking the cycle down into phases and figuring out where in the sequence prosthetics devices could be improved, designers have added features and materials that let users walk safely and comfortably with their own natural gait.



Designing a better prosthetic leg

In many prosthetic leg designs, the knee is the component that controls how the device operates. In the past, most designs were basic and relied on the *user* learning how to walk properly. This effort required up to 80% more energy than a normal gait and often made walking with an older prosthetic leg a work out!

The knee joint in those older designs was often a hinge that let the lower leg swing back and forth. The hinge could also lock in place to keep the leg straight and support the user's weight to make standing easier. This type of system worked relatively well on level surfaces, but could be difficult to use on inclines, stairs, slightly irregular terrain (like a hiking trail), or slippery surfaces.



Current prosthetic legs have improved upon old designs by employing hydraulics, carbon fiber, mechanical linkages, motors, computer microprocessors, and innovative combinations of these technologies to give more control to the user. For example, in some designs a device called a damper helps to control how fast the lower leg can swing back and forth while walking. The damper accomplishes this by changing the knee's resistance to movement as needed.

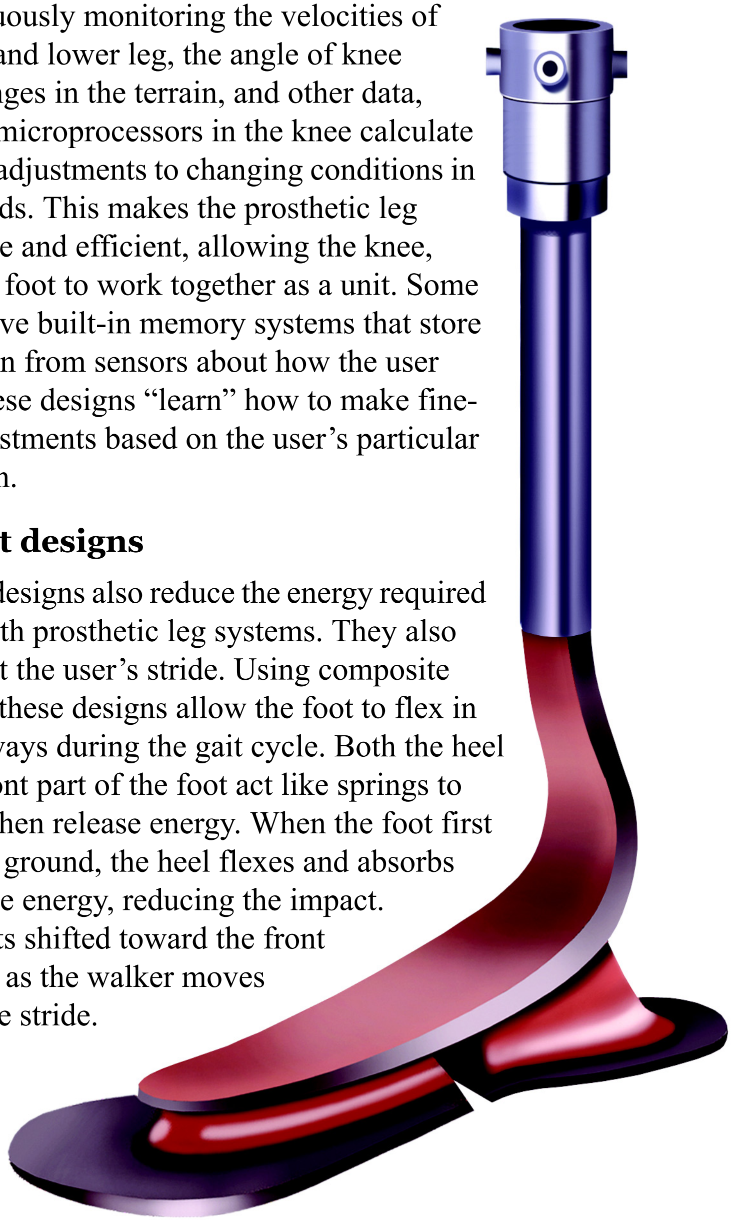
New knee designs allow users to walk, jog, and with some models even run with a more natural gait. In fact, in 2003 Marlon Shirley became the first above-the-knee amputee in the world to break the 11-second barrier in the 100-meter dash with a time of 10.97 seconds! She accomplished this feat with the aid of a special prosthetic leg designed specifically for sprinting.

Designs that learn

By continuously monitoring the velocities of the upper and lower leg, the angle of knee bend, changes in the terrain, and other data, computer microprocessors in the knee calculate and make adjustments to changing conditions in milliseconds. This makes the prosthetic leg more stable and efficient, allowing the knee, ankle, and foot to work together as a unit. Some designs have built-in memory systems that store information from sensors about how the user walks. These designs “learn” how to make fine-tuned adjustments based on the user’s particular gait pattern.

New foot designs

New foot designs also reduce the energy required to walk with prosthetic leg systems. They also smooth out the user’s stride. Using composite materials, these designs allow the foot to flex in different ways during the gait cycle. Both the heel and the front part of the foot act like springs to store and then release energy. When the foot first strikes the ground, the heel flexes and absorbs some of the energy, reducing the impact. Weight gets shifted toward the front of the foot as the walker moves through the stride.



As this happens, the heel springs back into shape and the energy released helps to flex the front part of the foot, once again storing energy. When the foot leaves the ground in the next part of the gait cycle, the flexed front part of the foot releases its' stored energy and helps to push the foot forward into the next stride.

Designers have realized the advantage of making highly specialized feet that match and sometimes exceed the capabilities of human feet. Distance running and sprinting feet are built to different specifications to efficiently deal with the forces and demands related to these activities.

A rock-climbing inventor

Hugh Herr, Ph.D., a physicists and engineer at the Harvard-MIT Division of Health Sciences and Technology (Boston, Massachusetts), studies biomechanics and prosthetic technology. In addition to holding several patents in this field, he has developed highly specialized feet for rock climbing that are small and thin—ideal for providing support on small ledges. Being an accomplished climber and an amputee allows Herr to field test his own inventions. While rock climbing, he gains important insights into the effectiveness and durability of each design.

Questions:

1. What are some technologies used by designers of prosthetic legs to improve their designs?
2. How are computers used to improve the function of prosthetic devices?
3. Explain how new foot designs reduce the amount of energy required to walk with a prosthetic leg.
4. Research the field of biomechanics. In a paragraph: (1) describe what the term “biomechanics” means, and (2) write about a biomechanics topic that interests you.

Chapter 4 Review

Understanding Vocabulary

Select the correct term to complete the sentences.

mechanical advantage	input arm	output
machine	horsepower	power
irreversible	input	simple machines
watt	work	efficiency
tension	fulcrum	

Section 4.1

1. A unit of power equal to 746 watts is called one ____.
2. ____ is the rate of doing work.
3. Force multiplied by distance is equal to ____.
4. The measurement unit of power equal to one joule of work performed in 1 second is called the ____.

Section 4.2

5. The ramp, the lever, and the wheel and axle are examples of ____.
6. Pushing on the pedals of a bicycle is an example of the ____ to a machine.
7. Moving a heavy load is an example of the ____ from a lever.
8. To calculate a machine's ____, you divide the output force by the input force.
9. A ____ is a device with moving parts that work together to accomplish a task.
10. The pivot point of a lever is known as its ____.
11. The side of a lever where the input force is applied is the _____.
12. The pulling force in a rope is known as ____.

Section 4.3

13. ____ is the ratio of work output to work input and is usually expressed as a percent.
14. A process with less than 100% efficiency is _____.

Reviewing Concepts

Section 4.1

1. Why are work and energy both measured in joules?
2. If you lift a box of books one meter off the ground, you are doing work. How much more work do you do by lifting the box 2 meters off the ground?
3. Decide whether work is being done (using your physics definition of work) in the following situations:
    a. Picking up a bowling ball off the floor.
    b. Two people pulling with the same amount of force on each end of a rope.
    c. Hitting a tennis ball with a tennis racket.
    d. Pushing hard against a wall for an hour.
    e. Pushing against a book so it slides across the floor.
    f. Standing very still with a book balanced on your head.
4. In which direction should you apply a force if you want to do the greatest amount of work?
5. What is the difference between work and power?
6. What is the meaning of the unit of power called a watt?

Section 4.2

7. List five types of simple machines.
8. Which two types of simple machines are in a wheelbarrow?
9. A certain lever has a mechanical advantage of 2. How does the lever's output force compare to the input force?.
10. Can simple machines multiply input forces to get increased output forces? Can they multiply work input to increase the work output?
11. Draw a diagram of each of the three types of levers. Label the input force, output force, and fulcrum on each.

12. You and a friend pull on opposite ends of a rope. You each pull with a force of 10 newtons. What is the tension in the rope?
13. A pulley system has four strands of rope supporting the load. What is its mechanical advantage?
14. A screw is very similar to which other type of simple machine?

Section 4.3

15. Why can't the output work for a machine be greater than the input work? Explain.
16. Can a simple machine's efficiency ever be greater than 100%? Explain your answer.
17. List two examples of ways to increase efficiency in a machine.

Solving Problems

Section 4.1

1. Calculate the amount of work you do in each situation.
    a. You push a refrigerator with a force of 50 N and it moves 3 meters across the floor.
    b. You lift a box weighing 25 N to a height of 2 meters.
    c. You apply a 500 N force downward on a chair as you sit on it while eating dinner.
    d. You lift a baby with a mass of 4 kg up 1 meter out of her crib.
    e. You climb a mountain that is 1000 meters tall. Your mass is 60 kg.
2. Sal has a weight of 500 N. How many joules of work has Sal done against gravity when he reaches 4 meters high on a rock climbing wall?
3. You do 200 joules of work against gravity when lifting your backpack up a flight of stairs that is 4 meters tall. What is the weight of your backpack in newtons?
4. You lift a 200 N package to a height of 2 meters in 10 seconds.
    a. How much work did you do?
    b. What was your power?
5. One machine can perform 500 joules of work in 20 seconds. Another machine can produce 200 joules of work in 5 seconds. Which machine is more powerful?
6. Two cranes use rope and pulley systems to lift a load from a truck to the top of a building. Crane A has twice as much power as crane B.
    a. If it takes crane A 10 seconds to lift a certain load, how much time does crane B take to lift the same load?
    b. If crane B can do 10,000 joules of work in a minute, how many joules of work can crane A do in a minute?
7. An elevator lifts a 500 kg load up a distance of 10 meters in 8 seconds.
    a. Calculate the work done by the elevator.
    b. Calculate the elevator's power.

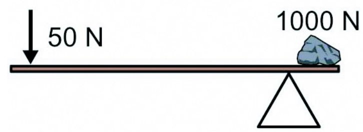
Section 4.2

8. A lever has an input force of 5 newtons and an output force of 15 newtons. What is the mechanical advantage of the lever?
9. A simple machine has a mechanical advantage of 5. If the output force is 10 N, what is the input force?
10. You use a rope and pulley system with a mechanical advantage of 5. How big an output load can you lift with an input force of 200 N?
11. A lever has an input arm 50 cm long and an output arm 20 cm long.
    a. What is the mechanical advantage of the lever?
    b. If the input force is 100 N, what is the output force?
12. You want to use a lever to lift a 2000 N rock. The maximum force you can exert is 500 N. Draw a lever that will allow you to lift the rock. Label the input force, output force, fulcrum, input arm, and output arm. Specify measurements for the input and output arms. State the mechanical advantage of your lever.
13. A rope and pulley system is used so that a 20 N force can lift a 60 N weight. What is the minimum number of ropes in the system that must support the weight?
14. A rope and pulley system has two ropes supporting the load.
    a. Draw a diagram of the pulley system.
    b. What is its mechanical advantage?
    c. What is the relationship between the input force and the output force?
    d. How much can you lift with an input force of 20 N?

15. You push a heavy car weighing 500 newtons up a ramp. At the top of the ramp, it is 2 meters higher than it was initially.
    a. How much work did you do on the car?
    b. If your input force on the car was 200 newtons, how long is the ramp?

Section 4.3

16. A lever is used to lift a heavy rock that weighs 1000 newtons. When a 50-newton force pushes one end of the lever down 1 meter, how far does the load rise?



17. A system of pulleys is used to lift an elevator that weighs 3,000 newtons. The pulley system uses three ropes to support the load. How far would 12,000 joules of input work lift the elevator? Assume the pulley system is frictionless.

Section 4.4

18. A 60 watt light bulb uses 60 joules of electrical energy every second. However, only 6 joules of electrical energy is converted into light energy each second.
    a. What is the efficiency of the light bulb? Give your answer as a percentage.
    b. What do you think happens to the "lost" energy?
19. The work output is 300 joules for a machine that is 50% efficient. What is the work input?
20. A machine is 75% efficient. If 200 joules of work are put into the machine, how much work output does it produce?

Applying Your Knowledge

Section 4.1

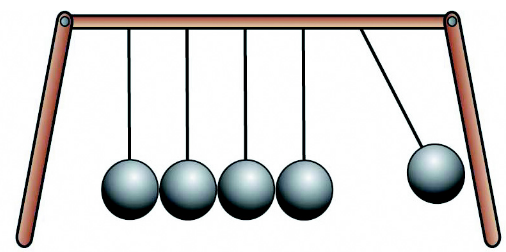
1. Imagine we had to go back to using horses for power. The power of one horse is 746 watts (1 horsepower). How many horses would it take to light up all the light bulbs in your school?
    a. First, estimate how many light bulbs are in your school.
    b. Estimate the power of each light bulb, or get it from the bulb itself where it is written on the top.
    c. Calculate the total power used by all the bulbs.
    d. Calculate how many horses it would take to make this much power.

Section 4.2

2. Look for simple machines in your home. List as many as you can find.
3. A car is made of a large number of simple machines all working together. Identify at least five simple machines found in a car.
4. Exactly how the ancient pyramids of Egypt were built is still a mystery. Research to find out how simple machines may have been used to lift the huge rocks of which the pyramids are constructed.

Section 4.3

5. A perpetual motion machine is a machine that, once given energy, transforms the energy from one form to another and back again without ever stopping. You have probably seen a Newton's cradle like the one shown below.



    a. Is a Newton's cradle a perpetual motion machine?
    b. According to the laws of physics, is it possible to build a perpetual motion machine?
    c. Many people have claimed to have built perpetual motion machines in the past. Use the internet to find one such machine. Explain how it is supposed to work and why it is not truly a perpetual motion machine.
6. A food Calorie is equal to 4184 joules. Determine the number of joules of energy you take in on a typical day.