Chapter 7

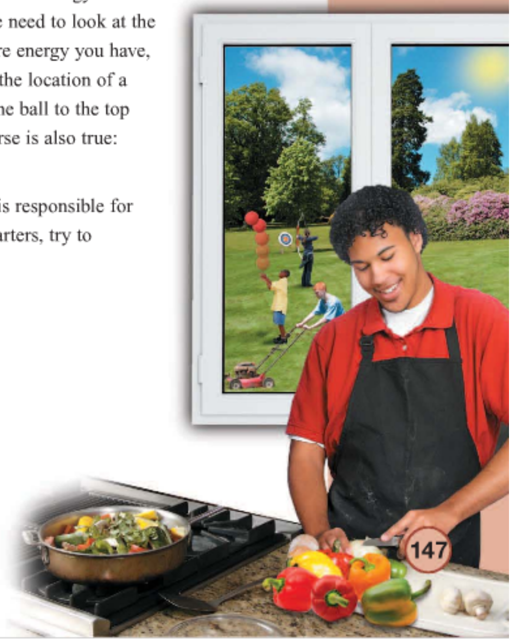
Work and Energy

What would it take to throw a ball all the way to the Moon? The Moon is 384,000 kilometers away from Earth. Even the best baseball pitcher in the world could not throw a ball to the moon, because it takes much more energy than any pitcher could produce. You could, however, throw a ball to the top of a telephone pole, which is only about 0.01 kilometers tall. The concept of energy explains how far a ball can be thrown above the ground, or how much light comes out of a bulb, or how hot the Sun gets. In fact, energy is responsible for all changes that occur in the physical world. Energy is what makes the universe active. To understand how and why things happen, we need to look at the flow of energy. If you have energy, you can make things change. The more energy you have, the bigger the changes can be, and the more work you can do. Changing the location of a ball from the ground to the Moon is a much larger change than moving the ball to the top of a telephone pole, and that's why it would take more energy. The converse is also true: If you have no energy at all, you can't make anything change.

Energy is everywhere! As you read this chapter, think about how energy is responsible for the changes that take place around you and even inside your body. For starters, try to identify the different forms of energy in the picture on this page.

Key Questions

- ✔ How does a physicist define work?
- ✔ What is energy, and what does it mean to conserve energy?
- ✔ Which is a more efficient machine: a bicycle or an automobile?



7.1 Force, Work, and Machines

In the last chapter, you saw how force and motion are related through Newton's laws of motion. Forces can be manipulated to accomplish physical tasks. How did ancient people move huge stones to build monuments, such as the Great Pyramid of Giza, long before the invention of trucks and engines? The ancient builders developed simple machines that allowed them to multiply by many times the force from their muscles. All simple machines obey a rule that says any advantage in force is compensated for by applying the force over a proportionally longer distance. This rule is an example of one of the most powerful laws in all of physics. The law involves the physics meaning of *work*, which you will explore in this section.

VOCABULARY

machine - a device with moving parts that work together to accomplish a task.

input - forces, energy, or power supplied to make a machine accomplish a task.

output - forces, energy, or power provided by the machine.

Using machines

What technology allows us to do

Machines allow us to do incredible things. Moving huge steel beams, digging tunnels that connect two islands, and building 100-story skyscrapers are examples. Clever human inventions of machines make this possible. A **machine** is a device, such as a bicycle, with moving parts that work together to accomplish a task (Figure 7.1). All the parts of a bicycle system work together to transform forces from your muscles into motion. A bicycle allows you to travel at faster speeds than you could on foot.

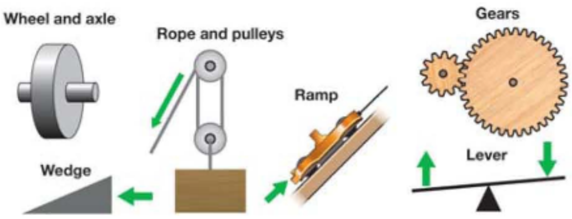
The concepts of input and output

For the machines in this chapter, the **input** includes everything you do to make the machine accomplish a task, such as pushing on the bicycle pedals. The **output** is what the machine does for you, such as going fast or climbing a steep hill. The input and output might be force, energy, or power. An electric saw uses your hand and electricity for input, and cuts wood for its output.

Figure 7.1: *A bicycle is a machine that allows you to travel faster than you can on foot.*

Simple machines

The beginning of technology The development of cars, airplanes, and other modern machines began with the invention of simple machines, such as levers. A **simple machine** is an unpowered mechanical device that accomplishes a task with only one movement. For example, a lever allows you to open a paint can, sweep the floor, or move a heavy rock (Figure 7.2). A variety of simple machines is shown below.



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 7.3 shows how a lever is arranged to create a large output force from a small input force. A **lever** is a stiff structure that rotates around a fixed point called a *fulcrum*.

Machines within machines Most of the machines we use today are made up of combinations of different types of simple machines. For example, a bicycle is a complex machine made up of simple machines. A bicycle uses wheels and axles, levers (the pedals and kickstand), and gears. A **gear** is a rotating wheel with teeth that receives or transfers motion and forces to other gears or objects. If you take apart a complex machine such as a clock, a food processor or blender, or a car engine, you will find it is made of simple machines, such as gears.

VOCABULARY

simple machine - an unpowered mechanical device that accomplishes a task with only one movement.

lever - a stiff structure that rotates around a fixed point called a fulcrum.

gear - a rotating wheel with teeth that transfers motion and forces to other gears or objects.

Figure 7.2: *Levers accomplish a task with one motion.*

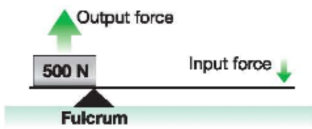


Figure 7.3: *If arranged like this, a lever can create a large output force.*

Mechanical Advantage

Mechanical advantage

Simple machines can manipulate input and output forces to create mechanical advantage for the user. **Mechanical advantage** is the ratio of output force to input force. If the mechanical advantage is bigger than one, the output force is bigger than the input force (Figure 7.4). A mechanical advantage smaller than one means the output force is smaller than the input force. For a typical automotive jack, the mechanical advantage is 30 or more. For a mechanical advantage of 30, a force of 100 newtons (22.5 pounds) applied to the input arm of the jack produces an output force of 3,000 newtons (675 pounds)—enough to lift one corner of an automobile.

MECHANICAL ADVANTAGE

$$MA = \frac{F_o}{F_i}$$

Mechanical advantage: MA; Output force (N): F_o; Input force (N): F_i

How mechanical advantage is created

If you use a jack to lift a car, you will notice that you have to move the arm of the jack a lot to raise the car only a little. Machines create mechanical advantage with trade-offs between force and distance. On the input of the jack, a small force has to move a large distance. On the output of the jack, a much larger force moves only a small distance. This trade-off, or inverse relationship between force and distance, is characteristic of all simple machines and is due to a powerful natural law in physics (conservation of energy).

Types of simple machines

There are a few basic kinds of simple machines that create mechanical advantage. The lever, wheel and axle, rope and pulleys, screw, ramp, and gears are the most common types. Complex machines such as a bicycle combine many simple machines into mechanical systems. A mechanical system is an assembly of simple machines that work together to accomplish a task.

VOCABULARY

mechanical advantage - ratio of output force to input force for a simple machine.

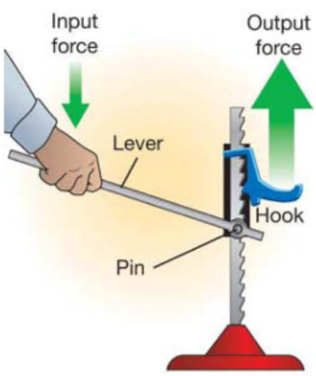


Figure 7.4: *This jack is an example of a lever. The input force is applied to the rigid bar. The output force is then applied by the machine to lift the car.*

Levers

Parts of the lever All levers include a stiff structure that rotates around a fulcrum. For example, you can make a lever by balancing a board on a log. The log is 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.

Mechanical advantage Levers are useful because you can arrange the fulcrum and the input and output arms to adjust the mechanical advantage of the lever. By changing the position of the fulcrum, you can alter the amount of input force needed to produce the desired output. For example, if the input arm is three times longer than the output arm, the output force is three times greater than the input force. This lever has a mechanical advantage of three. Using the length of the lever arms, mechanical advantage can be calculated by dividing the length of the input arm by the length of the output arm.

The three classes of levers Pliers, a wheelbarrow, and your arm each represent one of the three classes of levers. These objects all look different, so how are they similar? For starters, they all accomplish a task with one movement. They also all operate using a fulcrum and lever arms. Each class of levers is defined by the location of the input and output forces relative to the fulcrum (Figure 7.5 and Table 7.1).

Table 7.1: Classes of levers

Class of Lever	Fulcrum	Force	Length of Arms
1st	Between input and output forces	Vary in magnitude	Vary in length
2nd	One end of lever	Output > input	Input > output
3rd	One end of lever	Input > output	Output > input

Mechanical advantage of lever classes First-class levers can be set up to have a mechanical advantage of less than one, equal to one, or greater than one, depending on how long the input arm is compared to the output arm. Second-class levers have a longer input arm than output arm, and will have a mechanical advantage greater than one. Third-class levers have a mechanical advantage of less than one since the input arm is shorter than the output arm.

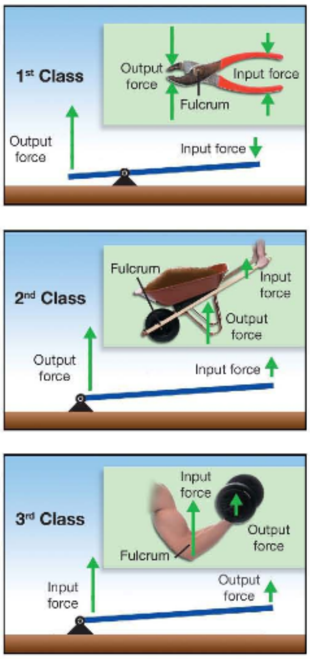


Figure 7.5: *These diagrams show the three classes of levers. What is the mechanical advantage of each of these levers: 1, > 1, or < 1?*

Work and machines

What *work* means in physics Simple machines obey a rule that says any advantage in force is compensated for by applying the force over a proportionally longer distance. When a force is applied over a distance, work can be done. The word *work* is used in many different ways. You can work on science problems, your toaster might not work, and taking out the trash might be too much work. In physics, however, work has a very specific meaning. **Work** is the transfer of energy that results from applying a force over a distance (Figure 7.6). If you push a box with a force of 1 newton for a distance of 1 meter, you do 1 joule of work. Both work and energy are measured in the same units (joules) because work is a form of energy.

Work is done by forces that cause movement When thinking about work, remember that work is done by forces that cause movement. If nothing moves (distance is zero), no work is done, even if a huge force is applied. Work is done only by the part of a force that acts in the same direction as the resulting motion. Force A in Figure 7.7 does no work at all because it does not cause the block to move sideways. Force B is applied at an angle to the direction of motion of the block. Only part of force B (in the direction the block moves) does work. The most effective force is force C. All of force C does work because force C acts in the same direction the block moves.

WORK

$$W = Fd$$

Work (J) W; Force (N) F; Distance in the direction of the force (m) d

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. It does not matter whether you lift the object straight up or you carry it up the stairs in a zig-zag pattern. The work is the same in either case.

VOCABULARY

work - a form of energy that comes from force applied over distance.

Figure 7.6: *Work is a form of energy you either use or get when a force is applied over a distance.*

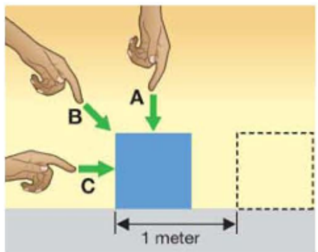


Figure 7.7: *All of force C does work.*

Solving Problems: Work

How much work is done by a person who pushes a cart with a force of 50 newtons if the cart moves 20 meters in the direction of the force (Figure 7.8)?

1. Looking for: You are asked for work.

2. Given: You are given values for force and distance.

3. Relationships: Work = force × distance.

4. Solution: The work done is: 50 N × 20 m = 1,000 J.

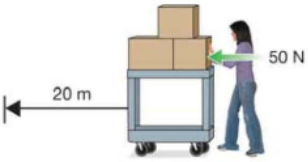


Figure 7.8: *How much work is this person doing by pushing the cart?*

Your turn...

a. How far does a 100-newton force have to move to do 1,000 joules of work?

b. An electric hoist does 500 joules of work lifting a crate 2 meters. How much force does the hoist use?

c. An athlete does one push-up. In the process, she moves half of her body weight, 250 newtons, a distance of 20 centimeters. This distance is the distance her center of gravity moves when she fully extends her arms. How much work did she do after one push-up?

d. You decide to push on a brick wall with all your strength for 5 minutes. You push so hard that you begin to sweat. However, the wall does not move. If you end up pushing with a force of 500 newtons, how much work did you do?

SOLVE FIRST LOOK LATER

a. 10 m

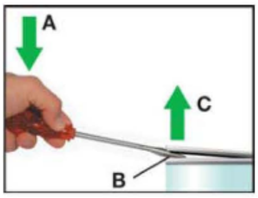
b. 250 N

c. 50 J

d. You didn't do any work because the wall did not move.

Section 7.1 Review

1. List two reasons from the section that explain why a simple machine is a useful device.
2. The arrangement of the lever in Figure 7.9 is similar to the arrangement you need to pry open the lid of a paint can. For the diagram to the right, label each part as *fulcrum*, *output force*, or *input force*.



3. Describe the term *mechanical advantage*. Why is it an important value to know when working with machines?
4. You might be surprised to learn that a broom is a lever. What kind of lever is it: first, second, or third class? Explain your answer.
5. What is the best way to define work?
   a. applying a force for a period of time
   b. moving a certain distance
   c. applying a force over a distance
   d. applying a force at a given speed
6. If you push a box across a table with a force of 5 newtons and the box moves 0.5 meter, how much work has been accomplished?
7. If you do 200 joules of work using a force of 50 newtons, over what distance was the force applied?
8. A cart was pulled for a distance of 1 kilometer. The amount of work accomplished equaled 40,000 joules. With what force was the work accomplished?
9. In which of these cases (Figure 7.10) is a waiter doing work on the object? Explain your answer.
   Situation 1: The waiter is carrying a tray of glasses across a room.
   Situation 2: The waiter is pushing a cart across a room.

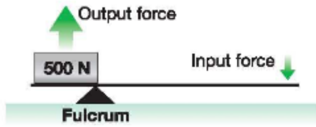


Figure 7.9: *Question 2.*

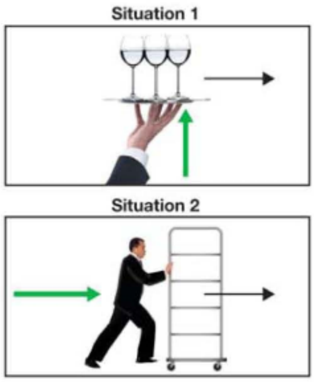


Figure 7.10: *Question 9.*