## 9.3 Simple Machines

### Section Learning Objectives

By the end of this section, you will be able to do the following:

- Describe simple and complex machines
- Calculate mechanical advantage and efficiency of simple and complex machines

### Teacher Support

**Teacher Support** The learning objectives in this section will help your students master the following standards:

- (6) Science concepts. The student knows that changes occur within a physical system and applies the laws of conservation of energy and momentum. The student is expected to:
  - (C) describe simple and complex machines and solve problems involving simple machines;
  - (D) define input work, output work, mechanical advantage, and efficiency of machines.

In addition, the High School Physics Laboratory Manual addresses content in this section in the lab titled: Work and Energy, as well as the following standards:

- (6) Science concepts. The student knows that changes occur within a physical system and applies the laws of conservation of energy and momentum. The student is expected to:
  - (D) demonstrate and apply the laws of conservation of energy and conservation of momentum in one dimension.

### Section Key Terms

### Teacher Support

**Teacher Support** In this section you will apply what you have learned about work to find the mechanical advantage and efficiency of simple machines.

[BL][OL] Ask the students what they know about machines and work. Dispel any misconceptions that machines reduce the amount of work. Be sure students do not equate machines and motors by asking for (and, if necessary, providing) examples of machines that are not motorized. Explain that simple machines are often hand-held, and that they reduce force, not work.

[AL] Ask for recall of the formula $W = \mathbf{f}d$. Explain that the product of force and distance is critical to understanding simple machines. Because the amount of work is not changed, the term $\mathbf{f}d$ does not change, but force can decrease if distance increases. This is the underlying principle of all simple machines.

### Simple Machines

Simple machines make work easier, but they do not decrease the amount of work you have to do. Why can't simple machines change the amount of work that you do? Recall that in closed systems the total amount of energy is conserved. A machine cannot increase the amount of energy you put into it. So, why is a simple machine useful? Although it cannot change the amount of work you do, a simple machine can change the amount of force you must apply to an object, and the distance over which you apply the force. In most cases, a simple machine is used to reduce the amount of force you must exert to do work. The down side is that you must exert the force over a greater distance, because the product of force and distance, $\mathbf{f}d$, (which equals work) does not change.

Let's examine how this works in practice. In Figure 9.8(a), the worker uses a type of lever to exert a small force over a large distance, while the pry bar pulls up on the nail with a large force over a small distance. Figure 9.8(b) shows the how a lever works mathematically. The effort force, applied at $\mathbf{F_e}$, lifts the load (the resistance force) which is pushing down at $\mathbf{F}_r$. The triangular pivot is called the fulcrum; the part of the lever between the fulcrum and $\mathbf{F}_e$ is the effort arm, $L_e$; and the part to the left is the resistance arm, $L_r$. The mechanical advantage is a number that tells us how many times a simple machine multiplies the effort force. The ideal mechanical advantage, *IMA*, is the mechanical advantage of a perfect machine with no loss of useful work caused by friction between moving parts. The equation for *IMA* is shown in Figure 9.8(b).

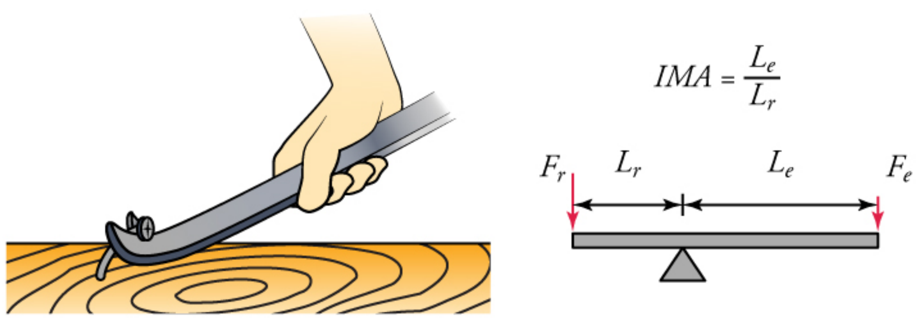


Figure 9.8 (a) A pry bar is a type of lever. (b) The ideal mechanical advantage equals the length of the effort arm divided by the length of the resistance arm of a lever.

In general, the $IMA$ = the resistance force, $\mathbf{F}_r$, divided by the effort force, $\mathbf{F}_e$. $IMA$ also equals the distance over which the effort is applied, $d_e$, divided by the distance the load travels, $d_r$.

$IMA = \frac{\mathbf{F}_r}{\mathbf{F}_e} = \frac{d_e}{d_r}$

Getting back to conservation of energy, for any simple machine, the work put into the machine, $W_i$, equals the work the machine puts out, $W_o$. Combining this with the information in the paragraphs above, we can write

$$W_i = W_o$$

$$\mathbf{F}_e d_e = \mathbf{F}_r d_r$$

$$\text{If } \mathbf{F}_e < \mathbf{F}_r, \text{ then } d_e > d_r.$$

The equations show how a simple machine can output the same amount of work while reducing the amount of effort force by increasing the distance over which the effort force is applied.

**Watch Physics**

**Introduction to Mechanical Advantage** This video shows how to calculate the $IMA$ of a lever by three different methods: (1) from effort force and resistance force; (2) from the lengths of the lever arms, and; (3) from the distance over which the force is applied and the distance the load moves.

Click to view content

**Teacher Support**

**Teacher Support** The beginning of this video may cause more confusion than illumination. It shows a derivation using trig functions that is beyond the scope of this chapter. Interested students may want to work their way through it. Most students should skip to the final two or three minutes which explain the basics of calculating $IMA$ of a lever from different ratios. Review $W = \mathbf{f}d$.

Watch Physics: Introduction to Mechanical Advantage. This video introduces simple machines, mechanical advantage and moments.

Click to view content

Two children of different weights are riding a seesaw. How do they position themselves with respect to the pivot point (the fulcrum) so that they are balanced?

a. The heavier child sits closer to the fulcrum.
b. The heavier child sits farther from the fulcrum.
c. Both children sit at equal distance from the fulcrum.
d. Since both have different weights, they will never be in balance.

Some levers exert a large force to a short effort arm. This results in a smaller force acting over a greater distance at the end of the resistance arm. Examples of this type of lever are baseball bats, hammers, and golf clubs. In another type of lever, the fulcrum is at the end of the lever and the load is in the middle, as in the design of a wheelbarrow.

**Teacher Support**

**Teacher Support** [AL]Tell students there are two other classes of levers with different arrangements of load, fulcrum, and effort. Ask them first to try to sketch these. After they have discovered the three kinds, with or without your help, ask if they can think of examples of the types not shown in Figure 9.8.

The simple machine shown in Figure 9.9 is called a wheel and axle**.** It is actually a form of lever. The difference is that the effort arm can rotate in a complete circle around the fulcrum, which is the center of the axle. Force applied to the outside of the wheel causes a greater force to be applied to the rope that is wrapped around the axle. As shown in the figure, the ideal mechanical advantage is calculated by dividing the radius of the wheel by the radius of the axle. Any crank-operated device is an example of a wheel and axle.

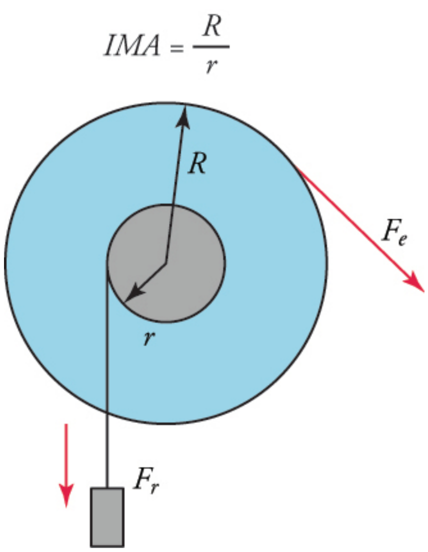


Figure 9.9 Force applied to a wheel exerts a force on its axle.

**Teacher Support**

**Teacher Support** [BL][OL] See if the students grasp the idea that a wheel and axle is really a type of lever. Show them that it looks more like a lever if the wheel is replaced by a crank. Give some examples: hand-powered windlass, steering wheel, door knob, and so on. Ask them why steering wheels had a greater diameter before power steering was invented.

[AL] Explain that wheels on vehicles are not really simple machines in the same sense as the one in Figure 9.9. The axle on a vehicle does not do work on a load. Energy loss to friction is reduced, but nothing is lifted.

An inclined plane and a wedge are two forms of the same simple machine. A wedge is simply two inclined planes back to back. Figure 9.10 shows the simple formulas for calculating the *IMA*s of these machines. All sloping, paved surfaces for walking or driving are inclined planes. Knives and axe heads are examples of wedges.

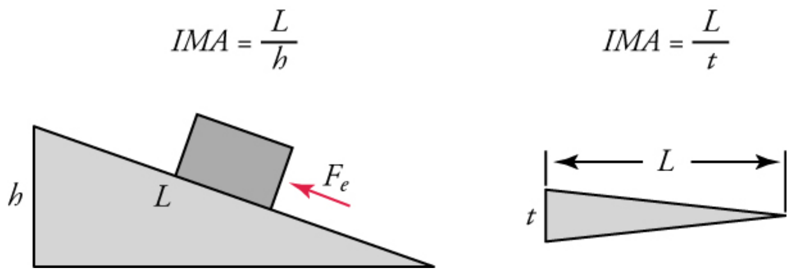


Figure 9.10 An inclined plane is shown on the left, and a wedge is shown on the right.

**Teacher Support**

**Teacher Support** [BL][OL] Talk about how inclined planes and wedges are similar and different. Note that, when using an inclined plane the load moves, but when using a wedge the load is stationary and the machine moves. Explain why more energy is usually lost to friction with these machines than with other simple machines.

The screw shown in Figure 9.11 is actually a lever attached to a circular inclined plane. Wood screws (of course) are also examples of screws. The lever part of these screws is a screw driver. In the formula for *IMA*, the distance between screw threads is called *pitch* and has the symbol *P*.

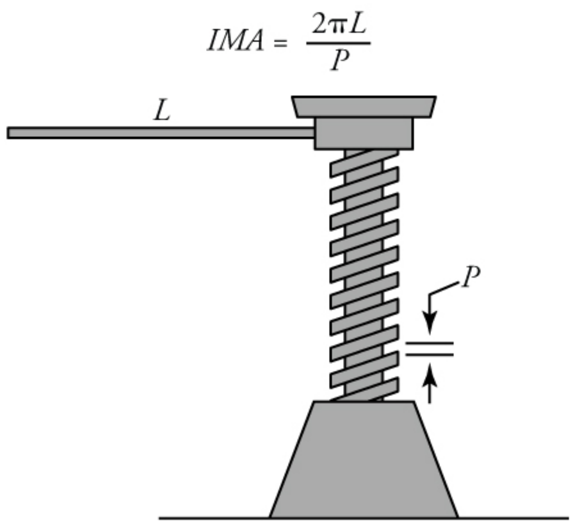


Figure 9.11 The screw shown here is used to lift very heavy objects, like the corner of a car or a house a short distance.

**Teacher Support**

**Teacher Support** [BL][OL] Suggest that a screw is classified as a separate type of simple machine perhaps because it looks so different from what it really is—an inclined plane which sometimes is turned by a lever. Explain that the combined mechanical advantage can be great. Devices like the one shown in Figure 9.10 are used to lift cars and even houses. Have the students compare this screw to a wood screw and a circular stairway.

[AL] Ask students how the forces exerted by a wood screw are different from those exerted by the screw in Figure 9.10. Ask for an explanation of the 2 in the equation for *IMA*.

Figure 9.12 shows three different pulley systems. Of all simple machines, mechanical advantage is easiest to calculate for pulleys. Simply count the number of ropes supporting the load. That is the *IMA*. Once again we have to exert force over a longer distance to multiply force. To raise a load 1 meter with a pulley system you have to pull *N* meters of rope. Pulley systems are often used to raise flags and window blinds and are part of the mechanism of construction cranes.

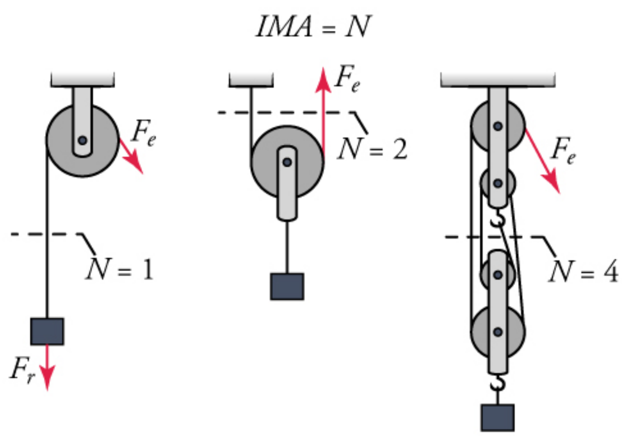


Figure 9.12 Three pulley systems are shown here.

**Teacher Support**

**Teacher Support** [BL][OL] The calculation for *IMA* of a pulley seems too easy to be true, but it is. Ask students to try to understand why *IMA* is simply *N*. Tell them that watching the video should make this point clear. Pulleys were once seen on sailing ships and farms, where they were used lift heavy loads. The overhang you may have seen on the end of old barn roofs is where a pulley was once attached. This way bales of hay could be lifted into the hay loft without getting wet. Pulleys can still be seen in use, most commonly on large building cranes.

**Watch Physics**

**Mechanical Advantage of Inclined Planes and Pulleys** The first part of this video shows how to calculate the *IMA* of pulley systems. The last part shows how to calculate the *IMA* of an inclined plane.

Click to view content

**Teacher Support**

**Teacher Support** Review what was learned about the *IMA* of inclined planes and pulley systems before watching the video. Remind the students that, for an ideal machine, work in = work out and that $W = \mathbf{f}d$. The video shows how to find the **f**s and the *d*s.

**Grasp Check**

How could you use a pulley system to lift a light load to great height?

a. Reduce the radius of the pulley.
b. Increase the number of pulleys.
c. Decrease the number of ropes supporting the load.
d. Increase the number of ropes supporting the load.

A complex machine is a combination of two or more simple machines. The wire cutters in Figure 9.13 combine two levers and two wedges. Bicycles include wheel and axles, levers, screws, and pulleys. Cars and other vehicles are combinations of many machines.

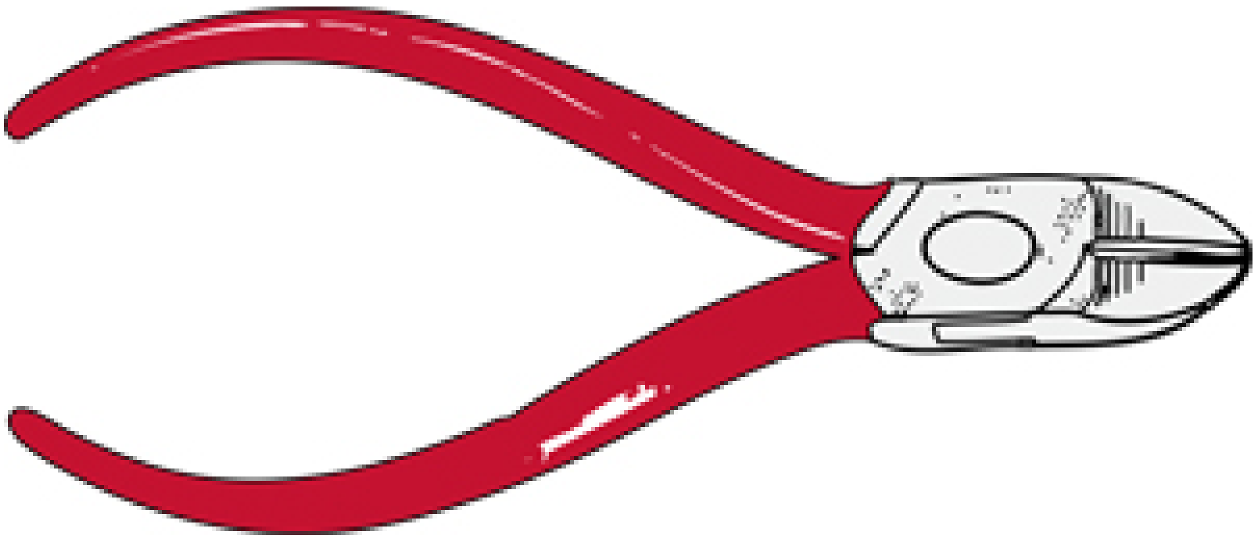

Figure 9.13 Wire cutters are a common complex machine.

**Teacher Support**

**Teacher Support** [BL][OL] Be sure students understand that a complex machine is just a combination of simple machines and is still fairly *simple*. Don't let them confuse the term with complicated machines such as computers. Note that the IMAs of the individual simple machines in a complex machine usually multiply because the output force of one machine becomes the input force of the other machine. For an additional fun activity, have the students search the Internet for *Rube Goldberg machine*.

### Calculating Mechanical Advantage and Efficiency of Simple Machines

In general, the *IMA* = the resistance force, $\mathbf{F}_\mathrm{r}$, divided by the effort force, $\mathbf{F}_\mathrm{e}$. *IMA* also equals the distance over which the effort is applied, $d_e$, divided by the distance the load travels, $d_r$.

$IMA = \frac{\mathbf{F}_r}{\mathbf{F}_e} = \frac{d_e}{d_r}$

Refer back to the discussions of each simple machine for the specific equations for the *IMA* for each type of machine.

No simple or complex machines have the actual mechanical advantages calculated by the *IMA* equations. In real life, some of the applied work always ends up as wasted heat due to friction between moving parts. Both the input work ($W_i$) and output work ($W_o$) are the result of a force, **F**, acting over a distance, *d*.

$W_i = \mathbf{F}_i d_i \text{and} W_o = \mathbf{F}_o d_o$

The efficiency output of a machine is simply the output work divided by the input work, and is usually multiplied by 100 so that it is expressed as a percent.

$\%\ \text{efficiency} = \frac{W_o}{W_i} \times 100$

Look back at the pictures of the simple machines and think about which would have the highest efficiency. Efficiency is related to friction, and friction depends on the smoothness of surfaces and on the area of the surfaces in contact. How would lubrication affect the efficiency of a simple machine?

**Teacher Support**

**Teacher Support** [BL][OL] Review the material on loss of mechanical energy to heat and the law of conservation of energy. Explain how heat lost because of friction assures that $W_o$ will always be less than $W_i$ preventing efficiency from ever reaching 100%.

**Worked Example**

**Efficiency of a Lever** The input force of 11 N acting on the effort arm of a lever moves 0.4 m, which lifts a 40 N weight resting on the resistance arm a distance of 0.1 m. What is the efficiency of the machine?

**Strategy**

State the equation for efficiency of a simple machine, $\%\ \text{efficiency} = \frac{W_o}{W_i} \times 100$, and calculate $W_o$ and $W_i$. Both work values are the product *Fd*.

Solution

$W_i = \mathbf{F}_i d_i = (11)(0.4) = 4.4$ J and $W_o = \mathbf{F}_o d_o = (40)(0.1) = 4.0$ J, then $\%\ \text{efficiency} = \frac{W_o}{W_i} \times 100 = \frac{4.0}{4.4} \times 100 = 91\%$

Discussion

Efficiency in real machines will always be less than 100 percent because of work that is converted to unavailable heat by friction and air resistance. $W_o$ and

$W_i$ can always be calculated as a force multiplied by a distance, although these quantities are not always as obvious as they are in the case of a lever.

**Teacher Support**

**Teacher Support** Teaching tip—When calculating efficiency, it is easy enough to understand what force in and force out are: the force you apply is force in and the weight of the object that is being lifted is force out. The input and output distances are easier to see for the lever, inclined plane and wedge. The other three are not as obvious. For a pulley system, the input distance is how far you pull the rope, and the output distance is the distance the load rises. For a wheel and axle, the input distance is the circumference of the wheel, and the output distance is the circumference of the axle. For a screw, the input distance is the circumference of the circle over which the force is applied, and the output distance is the distance between the screw threads.

**Practice Problems**

11.

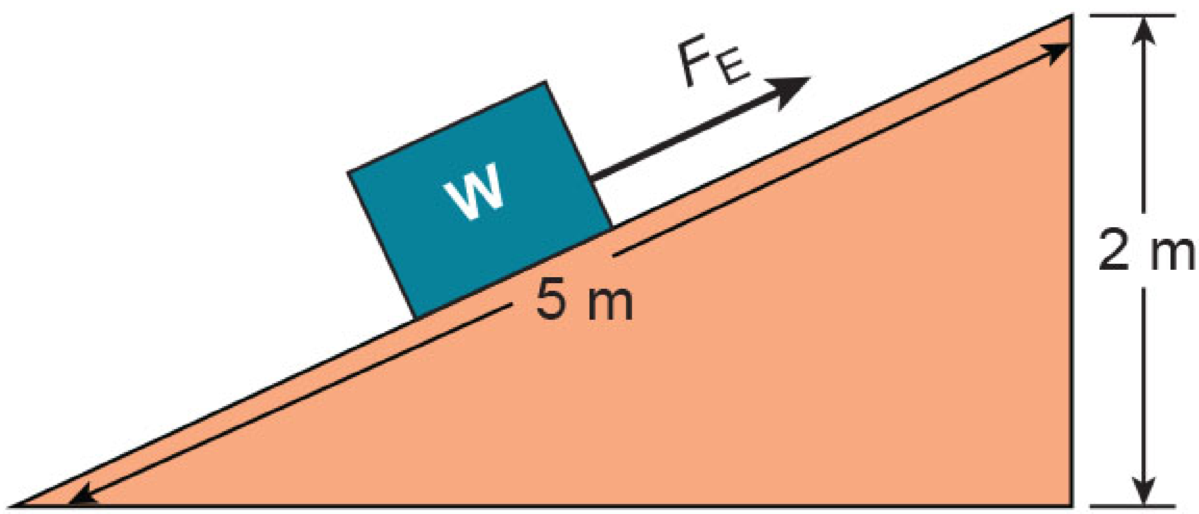


Figure 9.14

An inclined plane that is 5 m long and 2 m high is used to load a large crate into the back of a truck. What is the IMA of the inclined plane?

a. 0.4
b. 2.5
c. 0.4\,\text{m}
d. 2.5\,\text{m}

12.

If a pulley system can lift a 200N load with an effort force of 52 N and has an efficiency of almost 100 percent, how many ropes are supporting the load?

a. 1 rope is required because the actual mechanical advantage is 0.26.
b. 1 rope is required because the actual mechanical advantage is 3.80.
c. 4 ropes are required because the actual mechanical advantage is 0.26.
d. 4 ropes are required because the actual mechanical advantage is 3.80.

### Check Your Understanding

13.

True or false—The efficiency of a simple machine is always less than 100 percent because some small fraction of the input work is always converted to heat energy due to friction.

a. True
b. False

14.

The circular handle of a faucet is attached to a rod that opens and closes a valve when the handle is turned. If the rod has a diameter of 1 cm and the IMA of the machine is 6, what is the radius of the handle?

A. 0.08 cm
B. 0.17 cm
C. 3.0 cm
D. 6.0 cm

### Teacher Support

**Teacher Support** Use the Check Your Understanding questions to assess students' achievement of the section's learning objectives. If students are struggling with a specific objective, the Check Your Understanding will help identify which one and direct students to the relevant content.