Newton's Second Law

According to Newton's first law, a change in motion occurs only if a net force is exerted on an object. Newton's second law tells how a net force acting on an object changes the motion of the object. According to Newton's second law, a net force changes the velocity of the object and causes it to accelerate.

Newton's second law of motion states that if an object is acted upon by a net force, the acceleration of the object will be in the direction of the net force, and the acceleration equals the net force divided by the mass. According to the second law of motion, acceleration can be calculated from this equation:

Newton's Second Law

$$\textbf{acceleration} \text{ (in m/s}^2) = \frac{\textbf{net force} \text{ (in N)}}{\textbf{mass} \text{ (in kg)}}$$

$$a = \frac{F_{net}}{m}$$

Science Online

Topic: Sir Isaac Newton

Visit red.msscience.com for Web links to information about the contributions made to science and mathematics by Sir Isaac Newton.

Activity Make a time line to show what you learn.

Applying Math — Solve a Simple Equation

ACCELERATION OF A BASKETBALL You throw a 0.5-kg basketball with a force of 10 N. What is the ball's acceleration?

Solution

1. *This is what you know:*
   - mass: $m = 0.5$ kg
   - net force: $F_{net} = 10$ N
2. *This is what you need to know:* acceleration: $a = ?$ m/s^2
3. *This is the procedure you need to use:* Substitute the known values for the net force, F_{net}, and mass, m, into the equation for Newton's second law:

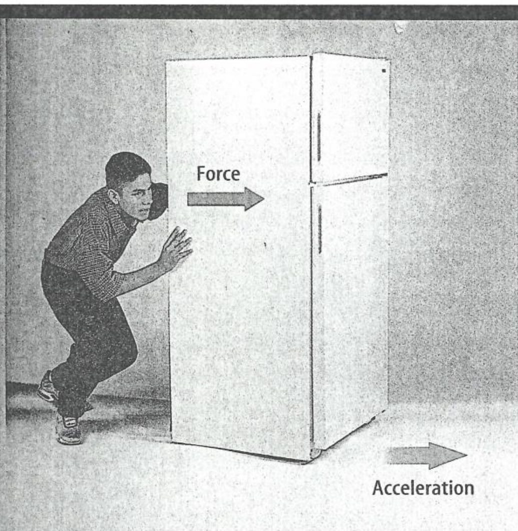
$$a = \frac{F_{net}}{m} = \frac{10\text{ N}}{0.5\text{ kg}} = 20\frac{\text{N}}{\text{kg}} = 20\text{ m/s}^2$$

4. *Check your answer:* Multiply your answer by the mass. You should get the force that was given.

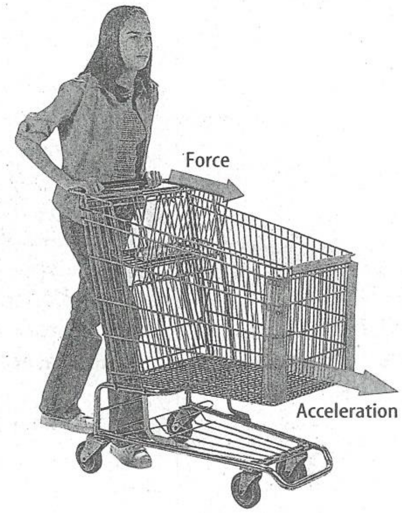
Practice Problems

1. You push a 20-kg crate with a force of 40 N. What is the crate's acceleration?
2. Calculate the acceleration of an 80-kg sprinter starting out of the blocks with a force of 80 N.

Science Online — For more practice, visit red.msscience.com/math_practice



When pushing a refrigerator, which has a large mass, a large force is required to achieve a small acceleration.



If you were to push an empty grocery cart with the same force, its acceleration would be larger.

Figure 11 The acceleration of an object depends on both the net force applied and the object's mass. **Compare** *the accelerations of a 900-kg car and a 12-kg bicycle if the same net force of 2,000 N is applied to each.*

Mass and Acceleration When a net force acts on an object, the object's acceleration depends on its mass. The more mass an object has, the more inertia it has, so the harder it is to accelerate. Imagine using the same force to push an empty grocery cart that you use to push a refrigerator, as shown in **Figure 11.** With the same force acting on the two objects, the refrigerator will have a much smaller acceleration than the empty cart. More mass means less acceleration if the force acting on the objects is the same.

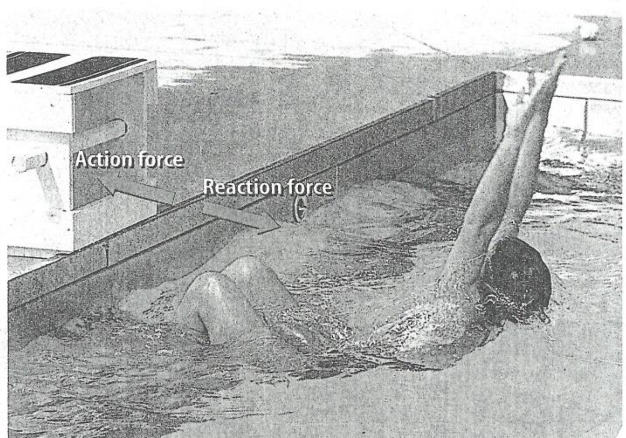
Newton's Third Law

Suppose you push on a wall. It might surprise you to know that the wall pushes back on you. According to Newton's third law, when one object exerts a force on a second object, the second object exerts an equal force in the opposite direction on the first object. For example, when you walk, you push back on the sidewalk and the sidewalk pushes forward on you with an equal force.

The force exerted by the first object is the action force. The force exerted by the second object is the reaction force. In **Figure 12,** the action force is the swimmer's push on the pool wall. The reaction force is the push of the pool wall on the swimmer. The action and reaction forces are equal, but in opposite directions.

Figure 13 on the next page shows how Newton's laws affect astronauts in space and the motion of the space shuttle.

Figure 12 When the swimmer pushes against the pool wall, the wall pushes back with an equal and opposite force.



Force Pairs Act on Different Objects If forces always occur in equal but opposite pairs, how can anything ever move? Won't the forces acting on an object always cancel each other? Recall that in Newton's third law, the equal and opposite forces act on different objects. When you push on the book, your force is acting on the book. When the book pushes back on you, its force is acting on you. One force of the force pair acts on the book, and the other force acts on you. Because the forces act on different objects, they don't cancel.

Reading Check *Why don't action and reaction forces cancel?*

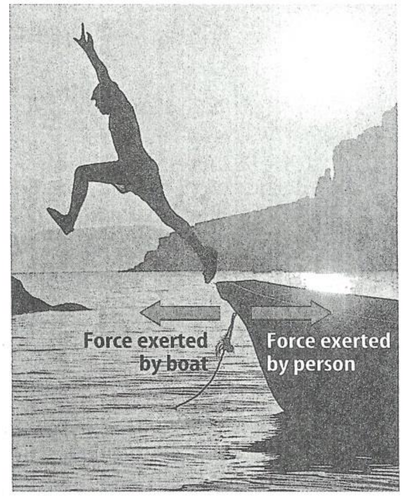


Figure 14 When you jump off a boat, your feet exert a force on the boat, which pushes it backward. The boat also exerts a force on your feet, which pushes you forward.

Examples of Newton's Third Law Think about what happens when you jump from a boat, as shown in **Figure 14.** If you jump off a small boat, the boat moves back. You are pushing the boat back with your feet with the same force with which it is pushing you forward. Because you have more mass than the boat, it will accelerate more than you do. When you jump off a big boat with a large mass, the force you exert on the boat gives it only a tiny acceleration. You don't notice the large boat moving, but the force it exerts on you propels you to the dock.

section 2 review

Force

- A force is a push or a pull.
- The net force is the combination of all the forces acting on an object.

Newton's Laws of Motion

- Newton's first law of motion states that an object's motion will not change unless a force acts on the object.
- Newton's second law of motion states that an object accelerates in the direction of the net force and that the acceleration can be calculated from this equation:

$$a = \frac{F_{net}}{m}$$

- Newton's third law of motion states that when an object exerts a force on another object, the second object exerts an equal and opposite force on the first object.

Self Check

1. **Explain** how the inertia of an object is related to the object's mass.
2. **Apply** If a force of 5 N to the left and a force of 9 N to the right act on an object, what is the net force?
3. **Infer** whether balanced forces must be acting on a car moving at a constant speed.
4. **Think Critically** A book sliding across a table slows down and comes to a stop. Explain whether this violates Newton's first law of motion.

Applying Math

5. **Calculate Net Force** Find the net force exerted on a 0.15-kg ball that has an acceleration of 20 m/s^2.
6. **Use a Spreadsheet** Enter the formula $a = F_{net}/m$ into a spreadsheet. Find the acceleration for masses from 10 kg to 200 kg. Graph your results.

section 3

Work and Simple Machines

as you read

What You'll Learn

- **Define** work.
- **Distinguish** the different types of simple machines.
- **Explain** how machines make work easier.

Why It's Important

Machines make doing work easier.

Review Vocabulary
radius: distance from the center of a circle to its edge

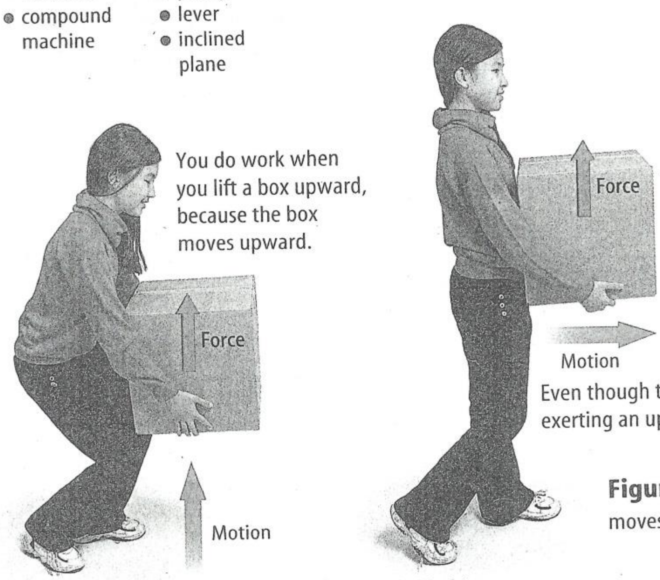
New Vocabulary
- work
- simple machine
- compound machine
- mechanical advantage
- pulley
- lever
- inclined plane

Work

Newton's laws explain how forces change the motion of an object. If you apply a force upward on the box in **Figure 15,** it will move upward. Have you done any work on the box? When you think of work, you might think of doing household chores or even the homework you do every night. In science, the definition of work is more specific—**work** is done when a force causes an object to move in the same direction as the force that is applied.

Effort Doesn't Always Equal Work If you push against a wall, do you do work? For work to be done, two things must occur. First, you must apply a force to an object. Second, the object must move in the same direction as the force you apply. If the wall doesn't move, no work is done.

Picture yourself picking up and carrying the box in **Figure 15.** You can feel your arms exerting a force upward as you lift the box. The box moves upward in the direction of your force, so you have done work. If you carry the box forward, you still can feel your arms applying an upward force on the box, but the box is moving forward. Because the direction of motion is not the same as the direction of the force applied by your arms, no work is done by your arms.



You do work when you lift a box upward, because the box moves upward.

Even though the box moves forward, your arms are exerting an upward force and do no work.

Figure 15 Work is done only when an object moves in the direction of the applied force.

Calculating Work

For work to be done, a force must be applied, and an object must move. The greater the force that is applied, the more work that is done. Which of these tasks would involve more work—lifting a shoe from the floor to your waist or lifting a pile of books the same distance? Even though the shoe and the books move the same distance, more work is done in lifting the books because it takes more force to lift the books. The work done can be calculated from the equation below.

Work Equation

work (in J) = **force** (in N) × **distance** (in m)

$$W = Fd$$

Work is measured in joules (J). The joule is named for James Prescott Joule, a nineteenth-century British physicist who showed that work and energy are related. Lifting a baseball from the ground to your waist requires about 1 J of work.

INTEGRATE Life Science

Muscles and Work Even though the wall doesn't move when you push against it, you may find yourself feeling tired. Muscles in your body contract when you push. This contraction is caused by chemical reactions in your muscles that cause molecules to move past each other. As a result, work is done by your body when you push. Research how a muscle contracts and describe what you learn in your Science Journal.

Applying Math — Solve a Simple Equation

WEIGHT LIFTING A weight lifter lifts a 500-N weight a distance of 2 m from the floor to a position over his head. How much work does he do?

Solution

1. *This is what you know:*
   - force: $F = 500$ N
   - distance: $d = 2$ m
2. *This is what you need to know:* work: $W = ?$ J
3. *This is the procedure you need to use:* Substitute the known values for force and distance into the work equation and calculate the work:
   $W = Fd = (500 \text{ N})(2 \text{ m}) = 1{,}000 \text{ N m} = 1{,}000 \text{ J}$
4. *Check your answer:* Divide your answer by the distance. You should calculate the force that was given.

Practice Problems

1. Using a force of 50 N, you push a computer cart 10 m across a classroom floor. How much work did you do?
2. How much work does an Olympic sprinter do while running a 200-m race with a force of 6 N?

Science Online — For more practice, visit red.msscience.com/math_practice

Figure 16 The can opener changes the small force of your hand on the handles to a large force on the blade that cuts into the can.

What is a machine?

How many machines have you used today? Why did you use them? A machine is a device that makes work easier. A can opener like the one in **Figure 16** is a machine that changes a small force applied by your hand into a larger force that makes it easier to open the can.

A **simple machine** is a machine that uses only one movement. A screwdriver is an example of a simple machine. It requires only one motion—turning. Simple machines include the pulley, lever, wheel and axle, inclined plane, wedge, and screw. A **compound machine** is a combination of simple machines. The can opener is a compound machine that combines several simple machines. Machines can make work easier in two ways. They can change the size of the force you apply. They also can change the direction of the force.

Reading Check *How do machines make work easier?*

Mechanical Advantage Some machines are useful because they increase the force you apply. The number of times the applied force is increased by a machine is called the **mechanical advantage** (MA) of the machine.

When you push on the handles of the can opener, the force you apply is called the input force (F_i). The can opener changes your input force to the force that is exerted by the metal cutting blade on the can. The force exerted by a machine is called the output force (F_o). The mechanical advantage is the ratio of the output force to the input force.

Mechanical Advantage Equation

$$\textbf{mechanical advantage} = \frac{\textbf{force out} \text{ (in N)}}{\textbf{force in} \text{ (in N)}}$$

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

Work In and Work Out In a simple machine the input force and the output force do work. For example, when you push on the handles of a can opener and the handles move, the input force does work. The output force at the blade of the can opener does work as the blade moves down and punctures the can.

An ideal machine is a machine in which there is no friction. Then the work done by the input force is equal to the work done by the output force. In other words, for an ideal machine, the work you do on the machine—work in—is equal to the work done by the machine—work out.

Science Online

Topic: Early Tools
Visit red.msscience.com for Web links to information about early tools.

Activity Write a short story about the nineteenth-century in which the characters use at least three early tools. Include at least one picture or description showing how the tools make work easier.

Increasing Force A simple machine can change a small input force into a larger output force. Recall that work equals force times distance. So, if the work in is equal to the work out, then smaller input force must be applied over a larger distance than the larger output force. Think again about the can opener. The can opener increases the force you apply at the handle. So the distance you move the handle is large compared to the distance the blade of the can opener moves as it pierces the can.

In all real machines, friction always occurs as one part moves past another. Friction causes some of the input work to be changed into heat, which can't be used to do work. So for a real machine, work out always will be less than work in.

The Pulley

To raise a window blind, you pull down on a cord. The blind uses a pulley to change the direction of the force. A **pulley** is an object, like a wheel, that has a groove with a rope or cable running through it. A pulley changes the direction of the input force. A rope thrown over a railing can be used as a pulley. A simple pulley, such as the one shown in **Figure 17,** changes only the direction and not the size of the force, so its mechanical advantage is 1.

It is possible to have a large mechanical advantage if more than one pulley is used. The double-pulley system shown in **Figure 17** has a mechanical advantage of 2. Each supporting rope holds half of the weight, so the input force you need to supply to lift the weight is half as large as for a single pulley.

Mini LAB

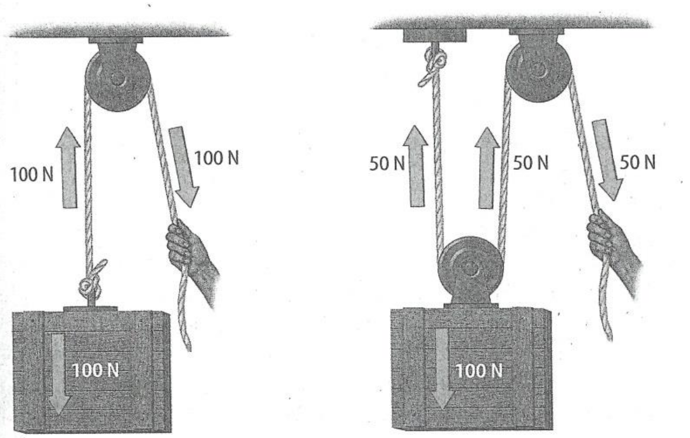
Observing Mechanical Advantage—Pulleys

Procedure

1. Tie a 3-m-long rope to the middle of a broomstick or dowel and hold this stick horizontally. Another student should hold another stick horizontally. Wrap the rope around both sticks four times, leaving about 0.5 m between the sticks.
2. A third student should pull on the rope while the other two students try to keep the sticks from coming closer together.
3. Observe what happens. Repeat using only two wraps of the rope and then using eight wraps.

Analysis

1. Describe what you observed. Could the students hold the sticks apart?
2. Compare and contrast the results with two, four, and eight turns of the rope around the sticks.

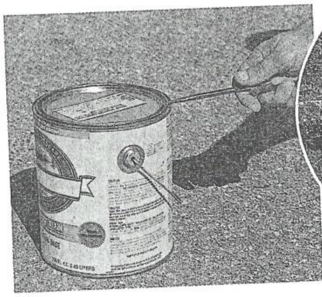


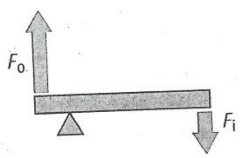
A single pulley changes the direction of the input force.

A combination of pulleys decreases the input force, so the mechanical advantage is greater than 1.

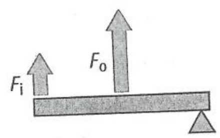
Figure 17 A pulley changes the direction of the input force and can decrease the input force.

Figure 18 A lever is classified according to the locations of the input force, output force, and fulcrum.

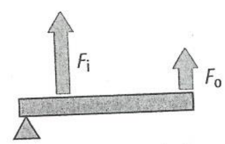




Sometimes a screwdriver is used as a first-class lever. The fulcrum is between the input and output forces.



A wheelbarrow is a second-class lever. The fulcrum is the wheel, and the input force is applied on the handles. The load, which is where the output force is applied, is between the input force and the fulcrum.



A hockey stick is a third-class lever. The fulcrum is your upper hand, and the input force is applied by your lower hand. The output force is applied at the bottom end of the stick.

The Lever

Probably the first simple machine invented by humans was the lever. A **lever** is a rod or plank that pivots about a fixed point. The pivot point is called the fulcrum. Levers can increase a force or increase the distance over which a force is applied. There are three types, or classes, of levers. The three classes depend on the positions of the input force, the output force, and the fulcrum.

The three classes of levers are illustrated in **Figure 18.** In a first-class lever, the fulcrum is located between the input force and output force. Usually, a first-class lever is used to increase force, like a screwdriver used to open a can.

If the output force is between the input force and the fulcrum, as in a wheelbarrow, the lever is a second-class lever. The output force always is greater than the input force for this type of lever.

A hockey stick is a third-class lever. In a third-class lever, the input force is located between the output force and the fulcrum. The mechanical advantage of a third-class lever always is less than 1. A third-class lever increases the distance over which the input force is applied.

The Wheel and Axle Try turning a doorknob by holding the narrow base of the knob. It's much easier to turn the larger knob. A doorknob is an example of a wheel and axle. Look at **Figure 19.** A wheel and axle is made of two round objects that are attached and rotate together about the same axis. The larger object is called the wheel, and the smaller object is the axle. The mechanical advantage of a wheel and axle can be calculated by dividing the radius of the wheel by the radius of the axle.

Reading Check *How do the lever, pulley, and wheel and axle make work easier?*

The Inclined Plane

An **inclined plane** is a sloped surface, sometimes called a ramp. It allows you to lift a heavy load by using less force over a greater distance. Imagine having to lift a couch 1 m off the ground onto a truck. If you used an inclined plane or ramp, as shown in **Figure 20,** you would have to move the couch farther than if you lifted it straight up. Either way, the amount of work needed to move the couch would be the same. Because the couch moves a longer distance up the ramp, doing the same amount of work takes less force.

The mechanical advantage of an inclined plane is the length of the inclined plane divided by its height. The longer the ramp is, the less force it takes to move the object. Ramps might have enabled the ancient Egyptians to build their pyramids. To move limestone blocks having a mass of more than 1,000 kg each, archaeologists hypothesize that the Egyptians built enormous ramps.

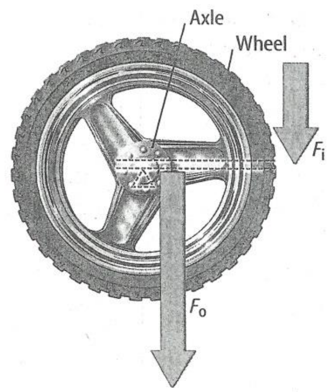


Figure 19 The radius of the wheel is greater than the radius of the axle. The mechanical advantage of the wheel and axle is greater than 1 because the radius of the wheel is greater than the radius of the axle.

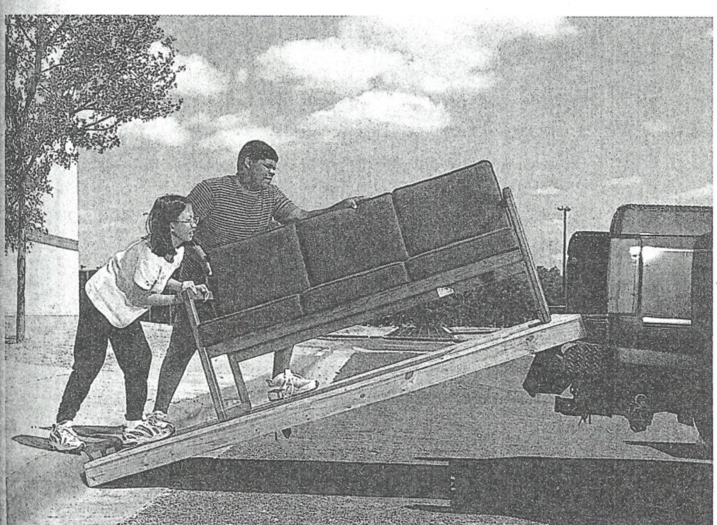
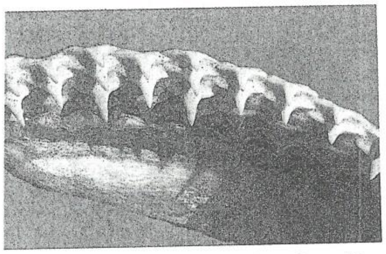
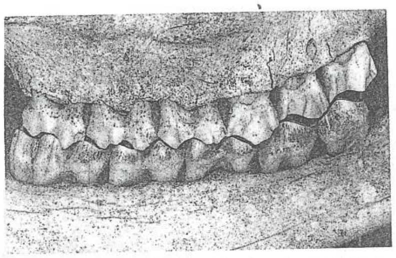


Figure 20 It is much easier to load this couch into a truck using a ramp. Even though the couch must be pushed a greater distance, less force is required.

Figure 21 Plant-eaters and meat-eaters have different teeth.



These wedge-shaped teeth enable a meat-eater to tear meat.



The teeth of a plant-eater are flatter and used for grinding.

INTEGRATE Life Science

The Wedge When you take a bite out of an apple, you are using wedges. A wedge is a moving inclined plane with one or two sloping sides. Your front teeth are wedges. A wedge changes the direction of the input force. As you push your front teeth into the apple, the downward input force is changed by your teeth into a sideways force that pushes the skin of the apple apart. Knives and axes also are wedges that are used for cutting.

Figure 21 shows that the teeth of meat-eaters, or carnivores, are more wedge-shaped than the teeth of plant-eaters, or herbivores. The teeth of carnivores are used to cut and rip meat, whereas herbivores' teeth are used for grinding plant material. Scientists can determine what a fossilized animal ate when it was living by examining its teeth.

The Screw A road going up a mountain usually wraps around the mountain. Such a road is less steep than a road straight up the side of the mountain, so it's easier to climb. However, you travel a greater distance to climb the mountain on the mountain road. The mountain road is similar to a screw. A screw is an inclined plane wrapped around a post. The inclined plane forms the screw threads. Just like a wedge, a screw also changes the direction of the force you apply. When you turn a screw, the input force is changed by the threads to an output force that pulls the screw into the material. Friction between the threads and the material holds the screw tightly in place.

section 3 review

Summary

Work

- Work is done when a object moves in the direction of the applied force.
- Work can be calculated from the equation $W = Fd$.

Simple machines

- Machines are devices that make work easier.
- Mechanical advantage is the number of times the input force is increased by a machine.
- A simple machine is a machine that does work with only one motion.
- The six simple machines are the pulley, lever, wheel and axle, inclined plane, wedge, and screw.

Self Check

1. **Describe** three different ways that using a machine makes doing work easier.
2. **Explain** why the output work is always less than the input work in a real machine .
3. **Compare** a wheel and axle to a lever.
4. **Think Critically** Identify two levers in your body. Which class of lever do the body levers belong to?

Applying Math

5. **Calculate Work** Find the work needed to lift a limestone block weighing 10,000 N a distance of 150 m.
6. **Calculate Input Force** Find the input force needed to lift a stone slab weighing 2,500 N using a pulley system with a mechanical advantage of 10.