9

Mechanical Power Systems

Basic Concepts

- List the six simple machines and give an example of each.
- List three types of gears.
- Name the two primary characteristics of power.
- Identify two mechanical transmission devices and describe how each operates.
- Define mechanical advantage and give an example.
- Recognize the difference between ideal mechanical advantage (IMA) and actual mechanical advantage (AMA).

Intermediate Concepts

- Discuss force and rate in a mechanical system.
- Describe the difference between scalar and vector quantities.

Advanced Concepts

- Design a mechanical system for a specific application.
- Predict the result of a mechanical system based on knowledge of balanced and unbalanced loads.
- Calculate the mechanical advantage of a simple machine.
- Compute the mechanical advantage of compound machines.
- Solve for the percentage of frictional loss in a mechanical system.

Mechanical systems produce work using one or more machines. Machines can change the size, direction, and speed of forces and can also change the type of motion produced. Sometimes, machines are needed to perform important functions, but very little force is necessary to produce work.

A block and tackle is a machine that enables a person to lift extremely heavy loads with little effort. This machine multiplies the force acting on it. A seesaw is a machine that changes direction of force. Pushing down on one end of the seesaw lifts the other end. An eggbeater changes the speed of an applied force. The blades of the beater move fast, even when you turn the crank slowly.

Machines and vehicles make use of three types of motion: reciprocating, rotary, and linear. See **Figure 9-1.** Reciprocating motion is back and forth along the same line. Rotary motion moves in circles. Linear motion is straight and in one direction.

Simple Machines

Complex machine: A machine that uses more than one simple machine to accomplish its tasks.

Simple machine: A lever, a pulley, a wheel and axle, an inclined plane, a screw, or a wedge.

When thinking of machines, washing machines, table saws, and drill presses may come to mind. These are examples of machines, but they are complex machines. ***Complex machines*** use more than one simple machine to accomplish their tasks and have multiple subsystems. We can study complex machines by identifying the smaller parts of each that actually perform different types of work using mechanical energy. These smaller parts are the ***simple machines***.

There are six simple machines used to control mechanical energy: the lever, the pulley, the wheel and axle, the inclined plane, the screw, and the wedge. See **Figure 9-2.** All six types of simple machines rely on the principles of only two: the lever and the inclined plane. The sections that follow explore the different simple machines you use every day.

Figure 9-1. Machines have three types of motion. A—Reciprocating. B—Rotary. C—Linear.

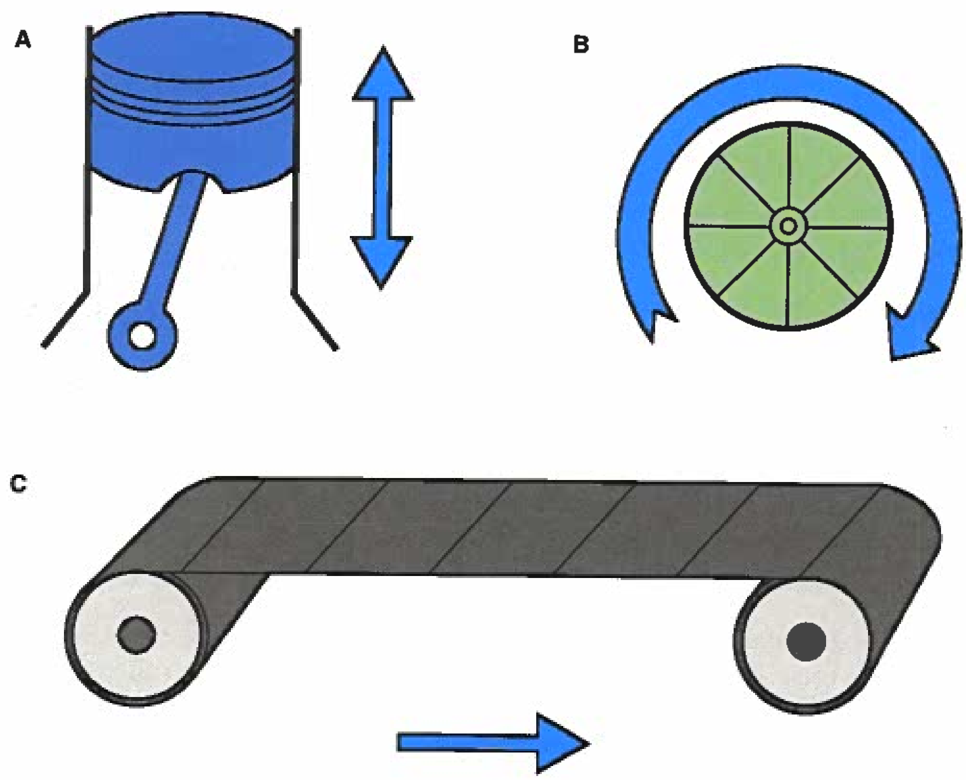
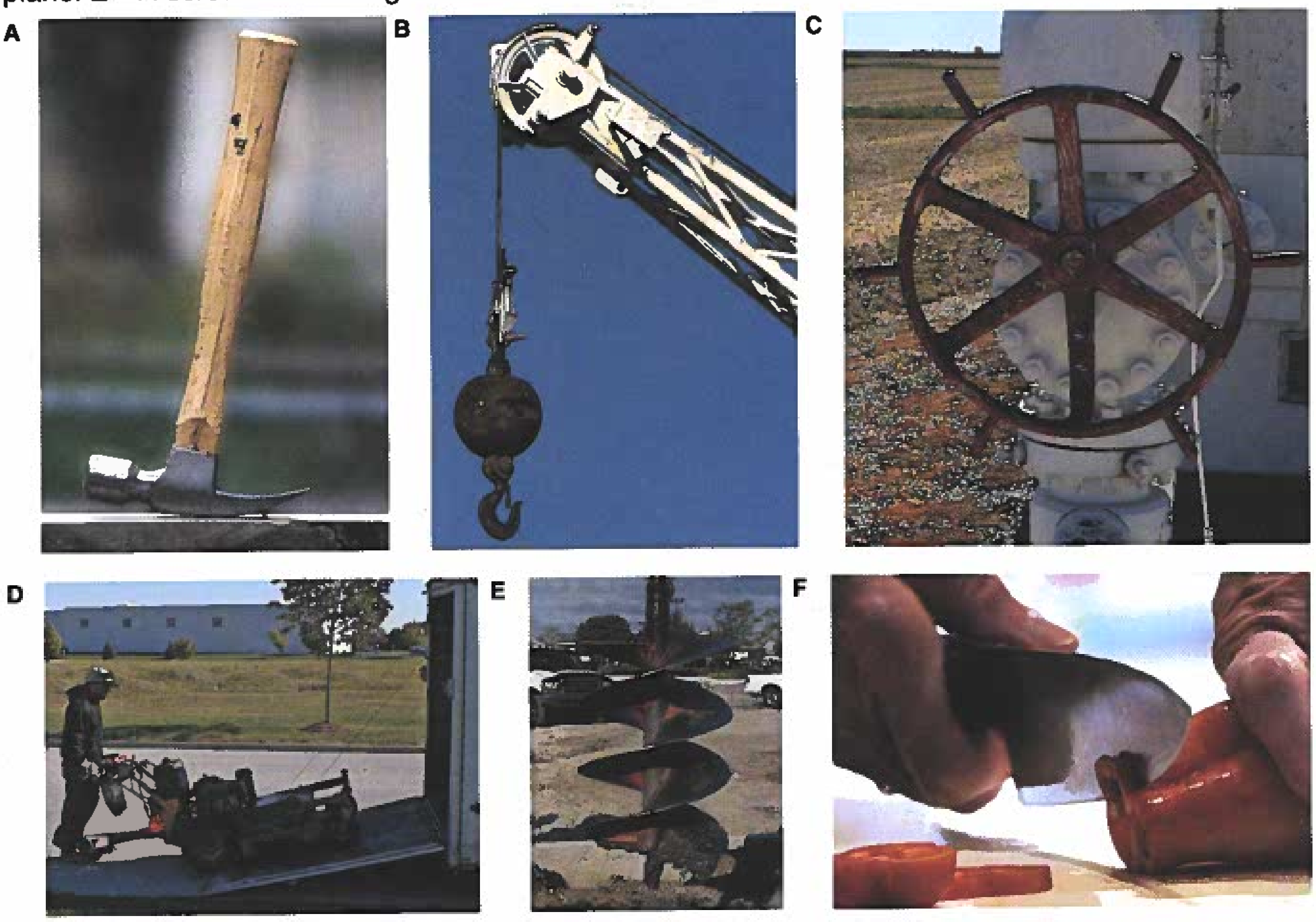


Figure 9-2. Six simple machines control all our mechanical energy. Compound machines are combinations of any of these six. A—A lever. B—A pulley. C—A wheel and axle. D—An inclined plane. E—A screw. F—A wedge.



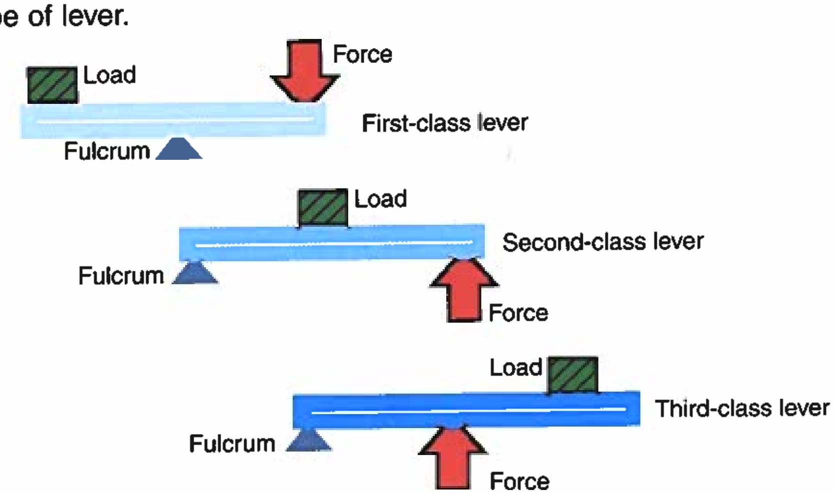
Levers

A ***lever*** is a rigid bar that rotates (turns) around one fixed point. The fixed point is called the ***fulcrum***. We use levers to apply force on loads. There are three classes of levers: first, second, and third. The position of the fulcrum, load, and input force determines the lever class. See **Figure 9-3.**

Lever: A rigid bar that rotates around one fixed point.

Fulcrum: The fixed point around which a lever rotates.

Figure 9-3. The relationship between the load, fulcrum, and force determines the type of lever.



Technology Link

Construction: Cranes

Cranes of various types and sizes can be found at almost any construction site. Some cranes are attached to delivery trucks so they can lift roof trusses into place or unload construction materials from the truck bed to the ground. Other cranes that are sometimes present at construction sites can rise hundreds of feet into the air to lift steel beams, concrete, and large tools onto the upper levels of a building under construction. These tower cranes must be assembled on the construction site, since they are too massive to transport. Tower cranes are especially impressive because they can often lift up to 20 tons of weight. They can also move that weight in or out, sometimes by more than 200′, and up or down, sometimes by hundreds of feet. To move this massive load requires tremendous mechanical advantage.

Before the crane ever arrives on-site, a pad for the crane is constructed. This pad can be as large as a 30′ square that is at least 4′ thick with reinforced concrete. It can weigh as much as 200 tons, forming a sturdy anchor for the crane base, which is bolted to the pad with the use of massive anchor bolts.

Next, the crane arrives in sections of steel that are constructed in triangulated fashion for increased strength. A mobile, truck-mounted crane is used to assemble the jib. The jib is the long horizontal working arm of the crane. It also contains the motor and machinery that allow the crane to operate and the counterweights necessary to stabilize the load when the crane is in use. The jib is then placed on a section or two of mast. At the top of the mast is a slewing unit, a gear-driven device that allows the crane to rotate. The mast is the upright section of the crane that allows it to stand tall. Each section of mast is about 20′ long. The assembly is placed onto the pad in the upright position and bolted down.

From this point, the crane must "grow itself" in height if it is required to be taller. Growing the crane is a three-step process. First, a weight is hung on the jib to balance the counterweight. Next, the slewing unit is detached and lifted by large hydraulic cylinders to the top of the mast. These hydraulic cylinders are capable of lifting the slewing unit more than 20′ above the top of the crane. The crane then lifts another section of mast into place between the top of the mast and the bottom of the slewing unit. When the jib and slewing unit are lowered, the crane is bolted back together with the mast, but this time it is 20′ taller. Using this technique, a freestanding tower crane can grow to more than 25 stories tall! It can also grow much taller if the mast is secured to the structural steel of the building it is helping to construct. This process can be repeated in reverse order when the crane is ready to be disassembled.

As for how the crane lifts a load, it is a balancing act between the working side of the jib and the counterweight or machinery side. A tower crane can safely lift more weight closer to the mast than it can as the load is transferred toward the far end of the jib. Can a tower crane become unbalanced enough to tip? It is unlikely because there are safety sensors to ensure that the crane does not become overloaded and unstable.

First-class lever: A lever that has the fulcrum positioned between the input force and the load.

First-class levers have the fulcrum positioned between the input force and the load. A seesaw is an example of a first-class lever. A screwdriver might be used as a first-class lever to open a can of paint. Pliers are an arrangement of two first-class levers using one fulcrum.

With ***second-class levers***, the load is placed between the fulcrum and the input force. A wheelbarrow is an example of a second-class lever. See **Figure 9-4.** Unlike first-class levers, second-class levers always provide an increase in force. They cannot, however, increase the distance the force moves.

Second-class lever: A lever that has the load placed between the fulcrum and the input force.

With ***third-class levers***, the input force is positioned between the fulcrum and the load. The distance the load is moved is greater than the movement of the input force. Many applications require increasing the distance, rather than the strength. Shovels, rakes, and other gardening tools use third-class levers. See **Figure 9-5.** Other examples include baseball bats, golf clubs, and hammers.

Figure 9-4. A wheelbarrow is a good example of a second-class lever. The fulcrum is the wheel, and the load is positioned between the wheel and the lifting force.

Pulleys

Pulleys consist of solid discs that rotate around a center axis. The discs usually have a groove around the outside edge that allows ropes or belts to easily ride around them. Pulleys are used to change forces in two ways:

- A single fixed pulley changes the direction of force. See **Figure 9-6.** Flags are raised on poles with the help of fixed pulleys.
- Single moveable pulleys change the size of a force. Moveable pulleys do not change the direction of the force. See **Figure 9-7.**

These simple machines operate on the principle of levers. This means they have an input force, a fulcrum, and a load. See **Figure 9-8.** Several pulleys used together make up a block and tackle. With several pulleys in the same system, the input force is greatly multiplied. Piano movers and construction workers use this type of system to lift heavy loads to great heights.

Figure 9-5. A third-class lever, such as this rake, is always a distance multiplier.

Wheels and Axles

The ***wheel and axle*** system is also based on the principle of levers. The large-diameter wheel and its small-diameter axle are attached to each other to move as one unit. Wheel and axle systems can be used to change the size or distance of a force. If the input force is applied to the wheel, it multiplies the turning force as it turns the axle. See **Figure 9-9.** The steering wheel of an automobile is an example of a wheel and axle system that resembles a second-class lever. See **Figure 10-10.**

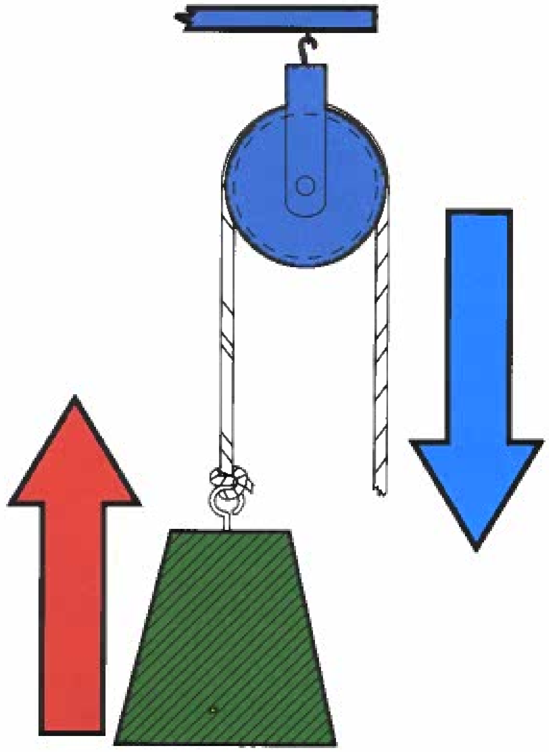


Figure 9-6. A fixed pulley changes the direction of force to lift a load.

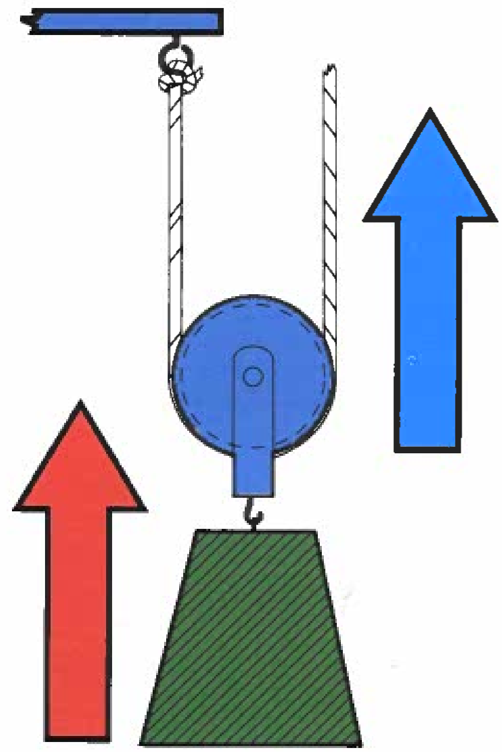


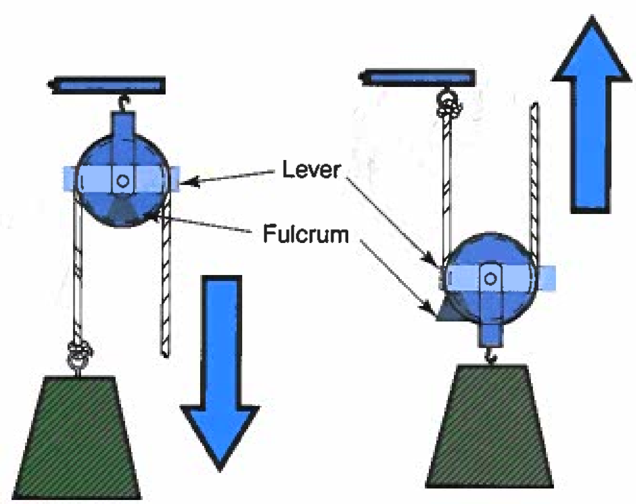
Figure 9-7. A moveable pulley does not change the direction of force.

Third-class lever: A lever that has the input force positioned between the fulcrum and the load.

Pulley: A solid disc that rotates around a center axis. It usually has a groove around the outside edge that allows ropes or belts to easily ride around them.

Wheel and axle: A large-diameter wheel and its small-diameter axle are attached to each other to move as one unit.

Figure 9-8. Pulleys operate like levers.



When the input force is applied to the axle, however, the applied force is transferred to the outside diameter of the wheel, and the distance it travels grows. See **Figure 9-11.** This action resembles a third-class lever. Doorknobs, screwdrivers, winches, and drills are a few of the common examples of wheel and axle systems.

Figure 9-9. The steering wheel of an automobile is a type of lever. It multiplies the force used to turn the front wheels.

Figure 9-10. Without the leverage of the steering wheel, it would be impossible to keep an automobile on a winding road.

Inclined Planes

An ***inclined plane*** is a simple machine that makes use of sloping surfaces. Loading ramps are an example of this simple machine. It is difficult for a person to lift a 100-lb. object up to the tailgate of a truck. See **Figure 9-12.** By rolling the object up a gently sloped ramp, much less force is exerted to achieve the same result. The one drawback in this system is that the amount of energy used is spread over a greater distance.

Inclined plane: A simple machine that makes use of sloping surfaces.

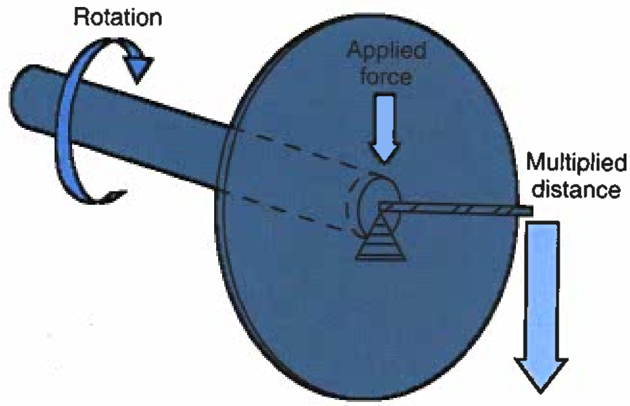


Figure 9-11. A wheel and axle is a distance multiplier when the force is applied to the smaller-diameter axle.

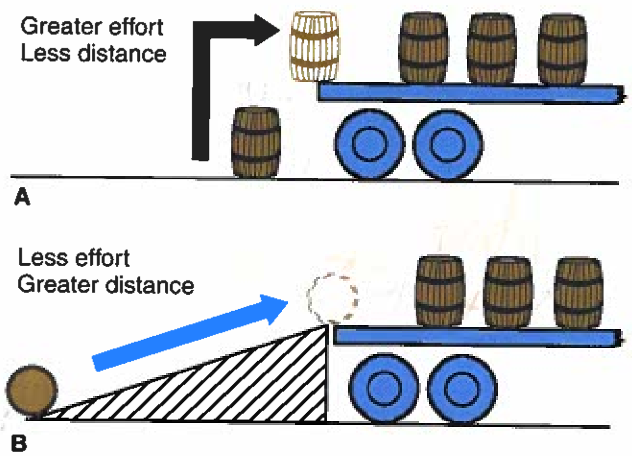


Figure 9-12. The inclined plane increases mechanical advantage. A—Greater force is needed to lift this barrel than to roll it up an incline. B—Rolling the barrel up a ramp (inclined plane) requires moving it a longer distance. Less force, however, is used. The inclined plane is a force multiplier.

Inclined planes are often found in the roads up steep hills or mountainsides. The roads switch back and forth, making a more gently angled slope. This allows vehicles going up to use less effort. See **Figure 9-13.** Wheelchair ramps use the same principle. Patients who use wheelchairs often have the necessary energy to negotiate a ramp, but would need assistance to mount steps.

Figure 9-13. The ramp that makes this community art center accessible to people with handicaps is a practical example of the inclined plane. To prevent a steep slope, the builder used a switchback design.

Screws

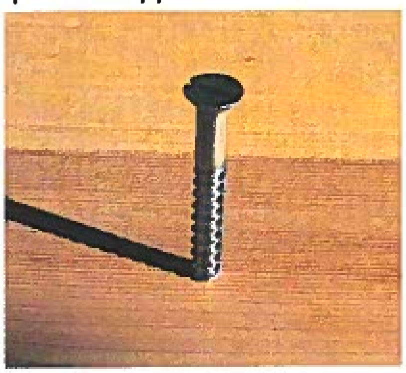
A *screw* is a simple machine that operates on the principle of inclined planes. It is a very long inclined plane wrapped around a shaft. See **Figure 9-14.** The longer the slope in the inclined plane on a screw, the more turns are required to advance 1" up its shaft. Screws that have 16 threads per inch apply greater force than screws that have 2 threads per inch. They also create more surface area to produce friction. Screws are commonly used as mechanical fasteners for wood, metal, and plastic. In this type of application, friction is desirable to grip and hold parts together better. When used in vises and car jacks, screws function as force multipliers.

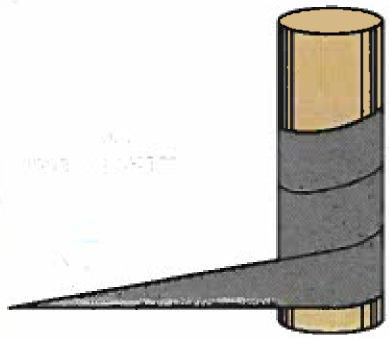
Screw: A simple machine consisting of a very long inclined plane wrapped around a shaft.

Wedge: A simple machine based on the principle of the inclined plane.

Gear: A metal wheel with small notches cut into its rim.

Figure 9-14. Looking at the threads on this screw, it is easy to see it is an inclined plane wrapped around a shaft.

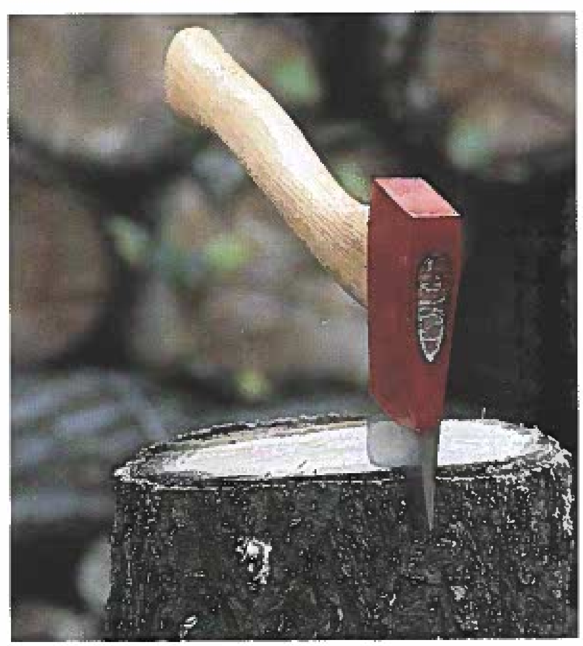




Wedges

A *wedge* is a simple machine consisting of two inclined planes placed back to back. Wedges are often used to split materials. See **Figure 9-15.** If you have ever driven a nail or chopped wood with a hatchet, you have used a wedge. As the hatchet enters the wood, it forces the wood fibers apart until they separate, or split.

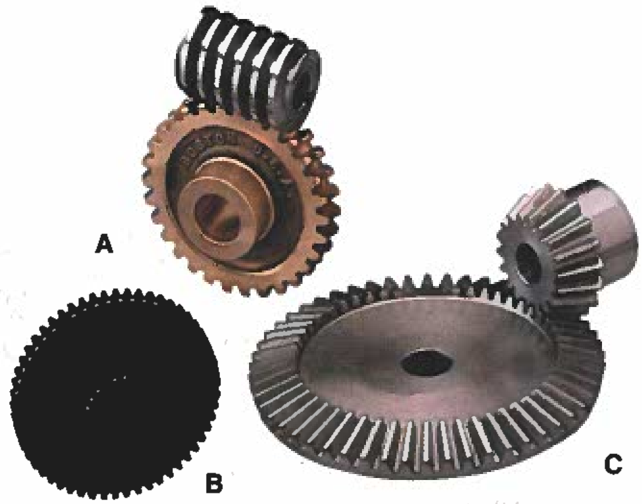
Figure 9-15. A hatchet uses the principle of a wedge. Its weight and fast movement combine to enable it to split the piece of wood.



Gears

A *gear* is a metal wheel with small notches, or teeth, cut into its rim. **Figure 9-16** shows some typical gears. Gear sets are made so the gear teeth interlock and drive each other. A gear powered by the engine or motor is referred to as the *drive gear.* The gear to which power is transferred is called the *driven gear.* As one tooth from the driver gear meshes with a tooth from the driven gear, power is transferred from the driver to the driven gear. A pair of gears is all that is needed to modify the characteristics of power coming from a hydraulic motor, an electric motor, or an internal combustion engine.

Figure 9-16. Several of the many types of gears available. A—A worm wheel. B—A spur gear. C—A bevel gear. (Boston Gear)



GREEN TECH
An example of an environmentally friendly system that produces mechanical power is the wind turbine. Wind energy can be harnessed and converted to mechanical power.

Although there are many different types of gears, the most common are the spur, helical, rack and pinion, worm, and bevel gears. Gears can control mechanical power in the same way as belts and pulleys—by changing the direction of power, speed, and torque. Like chains and sprockets, gears do not slip, and therefore they produce positive power transfer.

Characteristics of Mechanical Power

All forms of power, including mechanical power, have two primary characteristics: effort and rate. In a linear mechanical system, the effort is referred to as force and is usually measured in pounds, in the U.S. Customary system. In a rotary mechanical system, the effort characteristic is referred to as *torque* and is usually measured in foot-pounds (ft.-lbs.) or inch-pounds (in.-lbs.) for some low-torque applications.

The measurement of rate in a mechanical system varies, based on the application. Feet per second (fps) is a commonly used rate measurement for linear systems, such as conveyors and other material-processing and handling systems. Miles per hour (mph) is a measurement of linear mechanical rate associated with the automobile and is measured by the speedometer. Rate in a rotary mechanical system is usually measured in revolutions per minute (rpm) and is measured with a tachometer. Rotary mechanical rate may also be measured in revolutions per second (rps) or revolutions per hour (rph) in other, less common applications.

Quantities of Measurement

There are two categories of measurement for quantities: scalar quantity and vector quantity. A ***scalar quantity*** represents a physical quantity specified by the magnitude of the quantity and expressed by a number or unit. Examples include 75°F, 12.5 amperes, 65 mph, and 45 lbs. These types of expressions are referred to as scalar statements. Quantities that have both magnitude and direction are referred to as ***vector quantities***. There are three common vector quantities:

- ***Displacement*** includes both distance and direction. An example is 100 miles east.
- ***Velocity*** includes speed and direction. Some examples are 100 mph south and 25 fps east.
- Force includes the magnitude of the force (usually expressed in pounds) and the direction of the force. An example is 250 lbs. upward.

Scalar quantity: A physical quantity specified by the magnitude of the quantity and expressed by a number or unit.

Vector quantity: A quantity that has both magnitude and direction.

Displacement: A vector quantity that includes both distance and direction.

Velocity: A vector quantity that includes speed and direction.

Torque

Force that produces a twisting or turning effect or rotation is referred to as *torque* (torsional) force, or *moment force*. A torque measurement has two distinct components:

- A measurement of how much force is applied to the lever arm.
- A measurement of the radius of the lever arm itself. See **Figure 9-17.**

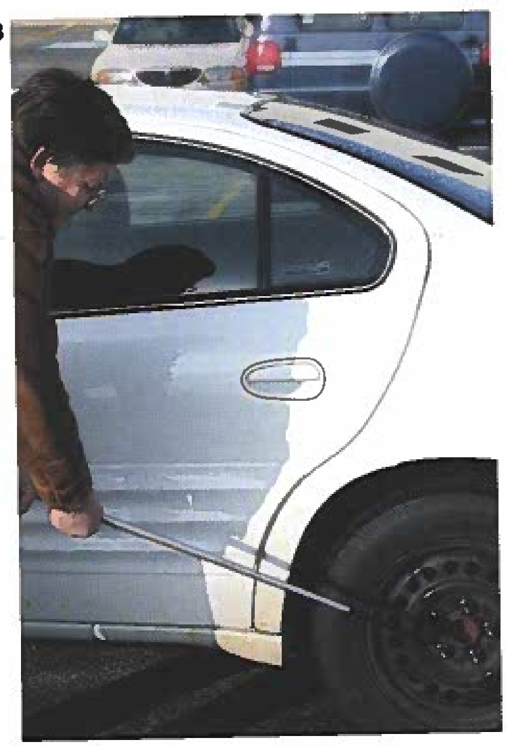
For example, picture a person trying to remove the lug nut that holds a wheel onto a car. The person generates 50 lbs. of force at a distance of

Figure 9-17. Torque can be increased by applying more effort or by extending the length of the lever. A—Applying 50 lbs. of effort to a 1.5′ lever does not generate enough torque to loosen the lug nut. B—Increasing the length of the lever to 3′ and applying the same amount of force doubles the torque and loosens the nut.

A

50 lbs. × 1.5′ = 75 ft.-lbs.

B



50 lbs. × 3′ = 150 ft.-lbs.

Prony brake: A device used to measure the effort produced by a twisting or turning force. It is based on the principle that if an opposite force equals the effort produced by a spinning object, movement will cease.

Indicated horsepower (ihp): The maximum potential hp produced by an engine under ideal conditions.

Brake horsepower (bhp): The amount of power available at the rear of the engine under normal conditions.

Frictional horsepower (fhp): The amount of hp necessary to overcome the internal friction of an engine and other forms of frictional loss.

1.5′ from the fulcrum of the wrench. If the lug nut does not move, there are two options to increase the torque applied to the bolt:

- Apply more force.
- Extend the effective lever arm of the wrench.

By increasing the length of the lever arm, more torque is generated when the same amount of force is applied.

It may be difficult to measure the effort produced by a twisting or turning force. An instrument more specific for the task than a simple spring scale must be used. For example, consider a flywheel attached to a pneumatic motor. The radius of the flywheel, one component of the torque measurement, is easily measured with a ruler. The second component in the measurement of torque is the force with which the flywheel is spinning. This can be obtained with a measuring device called a ***Prony brake.*** See **Figure 9-18.** The Prony brake is not a precise measuring instrument, but it will give a reasonable approximation of the force produced by a rotating shaft. It is based on a simple principle. If an opposite force equals the effort produced by a spinning object, movement will cease.

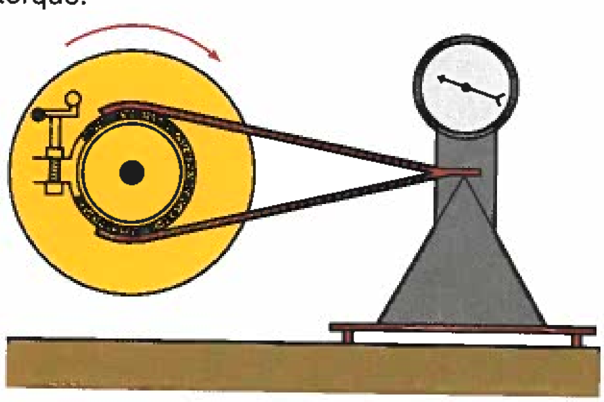
The Prony brake is adjustable and provides increasing tension on the flywheel until the flywheel stalls. At the moment the flywheel comes to a complete stop, the opposing force applied to it is approximately equal to the force with which the flywheel was spinning. A reading is taken from the scale and multiplied by the radius to determine the approximate torque produced by the flywheel.

Horsepower (hp)

Horsepower (hp) is the rate at which output work is performed. This unit of measurement was initially associated with mechanical power, but it is now commonly used to represent all forms of power, including fluid and electrical power. Today, devices that produce mechanical power, such as electric motors and internal combustion engines, are all rated in terms of their hp output. There are several different types of hp ratings:

- ***Indicated horsepower (ihp)*** is the maximum potential hp produced by an engine under ideal conditions.
- ***Brake horsepower (bhp)*** is the amount of power available at the rear of the engine under normal conditions.
- ***Frictional horsepower (fhp)*** is the amount of hp necessary to overcome the internal friction of an engine and other forms of frictional loss, such as tire resistance or wind drag. It represents the percentage of power inevitably lost within the internal workings of the engine and by other processes.

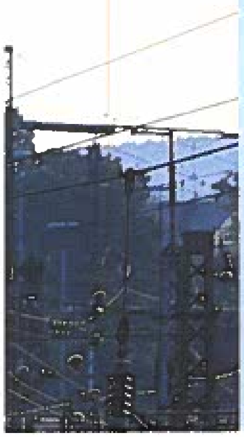
Figure 9-18. Using a Prony brake to measure torque.



Net Forces of Balanced and Unbalanced Loads

When forces are balanced, they are said to be in a state of equilibrium. This means that all movement ceases. Observe the two examples of how balanced forces create equilibrium shown in **Figure 9-19.**

Curricular Connection

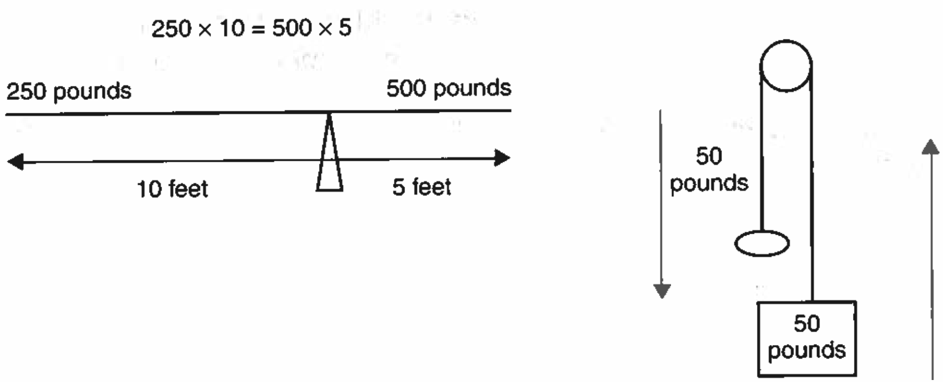


Social Studies: The History of Horsepower (hp)

James Watt, a Scottish engineer and inventor, coined the term *horsepower (hp)*. He developed this unit of power as a way of comparing machines to the existing form of power generation for work purposes, the horse. In the early days of the Industrial Revolution in England, horses were used to raise coal from the mines. Watt was working on improving the steam engine, and he tried to sell it to the coal companies to replace their horses. He wanted to know how powerful his new engines were, so he measured how long it took a horse to lift a weight a certain distance. Watt then compared this with how long it took his steam engine to lift the same weight the same distance.

After many tests with horses, he determined that a horse, on average, can haul coal at the rate of 22,000 ft.-lbs. per minute. He decided to raise this number by 50%, to err on the conservative side and, at the same time, make his engines seem more powerful than a horse so they would sell. Therefore, 33,000 ft.-lbs. per minute became the standard unit of measurement for linear mechanical hp. If an engine can push or pull 33,000 lbs. of load 1′ in 1 minute, it is a 1 hp engine. The energy outputs of cars, lawnmowers, vacuums, and nuclear power plants are all measured in hp.

Figure 9-19. Here are two balanced loads. The diagram on the right shows a fixed pulley. One fixed pulley creates only a change in direction, but no mechanical advantage. Pulling on the handle with 50 pounds of force will stabilize the load to provide equilibrium. Additional force will be necessary to create an imbalance and move the load.



When the forces of effort and opposition are totally balanced, no movement will occur. A change in effort creates an unbalanced load, which results in movement. When this type of imbalance results along a straight line, calculating the results is easily performed with simple addition and subtraction. Forces in parallel are simply added to create what is known as a resultant force. If you were pulling on the load in Figure 9-19 with 50 pounds of force and your friend was pulling with another 20 pounds of force, the resultant force would be 70 pounds of effort.

Transmission of Mechanical Energy

Compound machines make use of two or more simple machines. To transmit or pass power from one part of a vehicle to another, variations on these simple machines are used. The devices described in the following sections are specialized components in industrial machines and transportation vehicles. The operation of these devices relies on the principles of one or more simple machines.

Clutches

Clutch: A mechanical device that connects the power source to the rest of the machine.

A ***clutch*** is a mechanical device that connects the power source (a motor or engine) to the rest of the machine. In many transportation vehicles, the clutch connects the power system to the drive system. When the operator of the vehicle wants to disconnect these two systems, he simply engages the clutch. This device is needed so vehicles can remain at rest with the engine running, start slowly without stalling, and shift gears while moving.

Clutches operate on the principle of friction. Usually, two surfaces rub against each other and then lock against each other. This enables the two parts to move at the same speed, powered by one source. The two types of clutches widely used in transportation vehicles are the diaphragm clutch and the centrifugal clutch.

Pulleys and Belts

If you have ever looked under the hood of an automobile, you have probably seen many different belts that move around pulleys. See **Figure 9-20.** The belt and pulley systems under the hood of a car transmit

Career Connection

Mechanical Technicians

The power used in machines of mechanical systems produces work. Since the work machines do play such a large role in our daily lives, the equipment must function properly. Mechanical technicians are necessary to maintain and service machines.

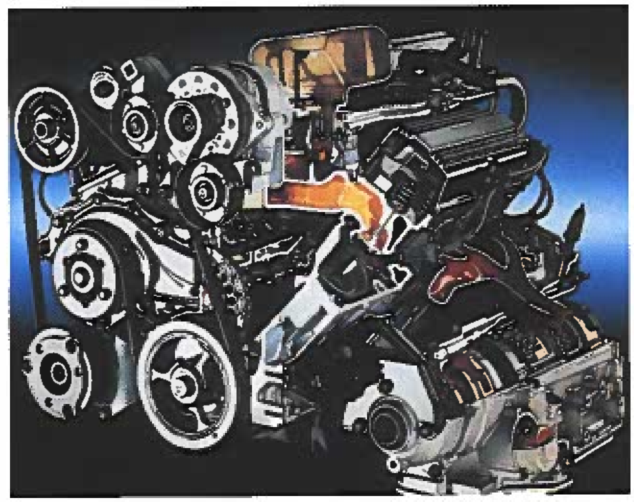
Maintenance of equipment can include monitoring, repair, and design of mechanical systems. Technicians may be responsible for preparing proposals and for sketching and designing equipment. Once the machines have been assembled, technicians subject the equipment to several tests. Testing may be conducted on machines already in use. Technicians determine from these tests whether improvement is needed. Machines also sometimes require repairs. Technicians must stay within safety limits when working with this equipment.

Technicians who design mechanical systems must have a thorough knowledge of engineering and design techniques. The ability to communicate their plans and ideas clearly is also important. To repair machines, technicians must understand mechanics and possess mathematical skills. An associate's degree is required to be a worker in this field. The yearly salary may range from $25,000 to $57,000.

power from the engine to drive engine components, such as the water pump and fan. Other belt and pulley systems are used to power accessories, such as air conditioning.

Belts and pulleys control mechanical energy through any of five different arrangements. Through their use, we can connect and disconnect power like a clutch, change direction, reverse rotation, change speed, and change torque. **Figure 9-21** illustrates the different arrangements to accomplish these tasks.

Figure 9-20. Automobile engines make use of belt and pulley systems. Older engines often had several belts driving different devices, but most modern engines, such as this one, use a single long belt called a *serpentine belt.*



Chains and Sprockets

The chain and sprocket setup shown in **Figure 9-22** is a very familiar sight. This mechanical transmission system is found on bicycles, mopeds, and motorcycles. Chains and sprockets are usually used as the drive system to bring power to the driving wheel of the vehicle.

Like belts and pulleys, chain and sprocket systems can change speed and torque. By shifting the chain to different sprockets on a bicycle, the input force can be controlled. Making this adjustment can make it easier to climb hills or deliver torque to the wheels when riding downhill. Chain and sprocket systems have an advantage over belt and pulley systems when used for drive systems. They provide positive power transfer, which means that the chain cannot slip like a belt on a pulley.

Figure 9-21. Pulley and belt arrangements transfer power from one point to another. They also can change torque and speed through pulley sizes. Sometimes, belts are used to change direction of a force.

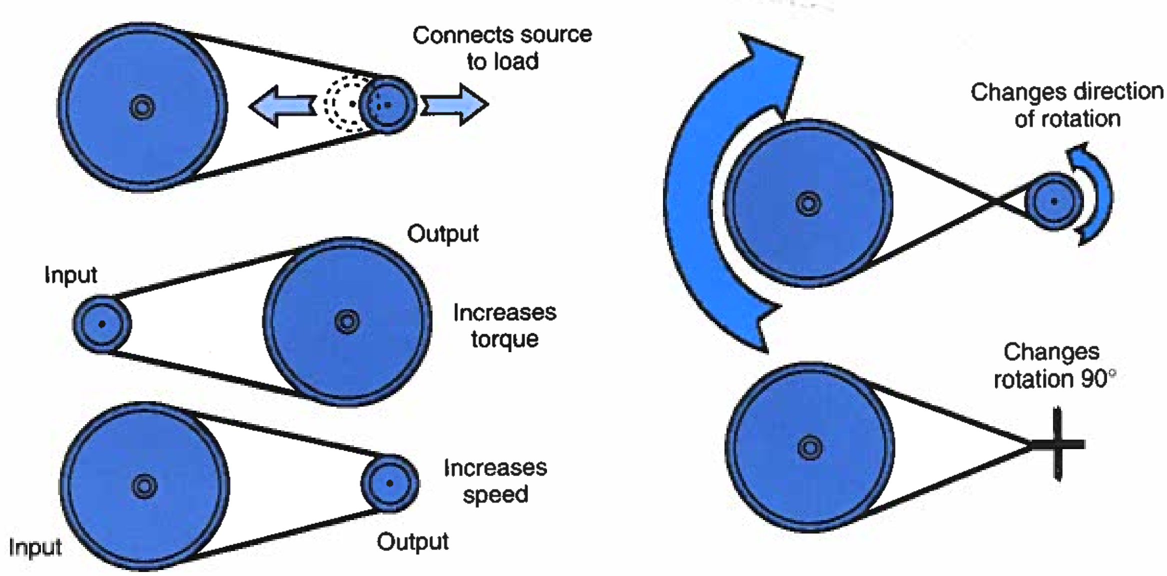
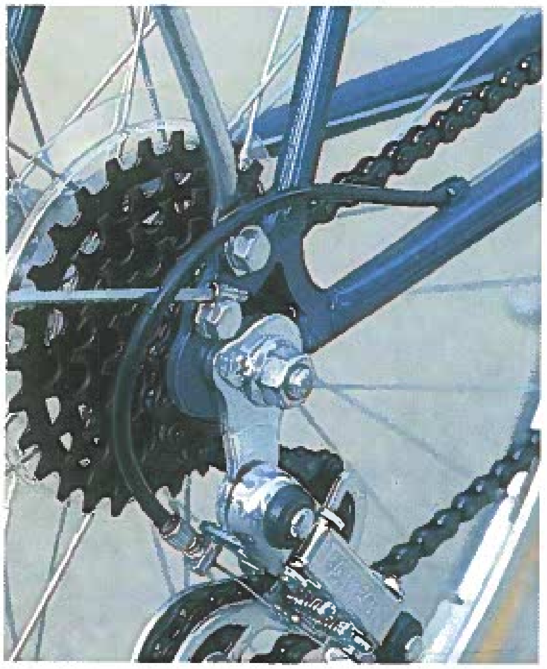


Figure 9-22. A chain and sprocket transfer power from the bicycle pedals to the rear wheel.



Shafts and Bearings

Shafts are long, cylindrical pieces of metal used to transfer mechanical energy in many types of machines. They are vital parts of automobile engines and drive systems. See **Figure 9-23.** Because of their solid construction, shafts permit positive power transfer.

Bearings are specially shaped pieces of metal used to support shafts and reduce friction between metal parts as they move past or revolve around each other. They are made to be strong, but they also allow the shaft to turn inside them. Although there are many types of bearings, the most common types in vehicles are smooth circles of metal shaped to exactly fit the outside of the shaft.

These are very important in the operation of any shaft-driven machine. They must conduct heat away from the shaft, as well as resist softening from heat. Bearings must also be soft enough to glide over uneven shaft surfaces and tough enough to resist the corrosive properties of some lubricants. **Figure 9-24** illustrates a typical shaft and bearing relationship.

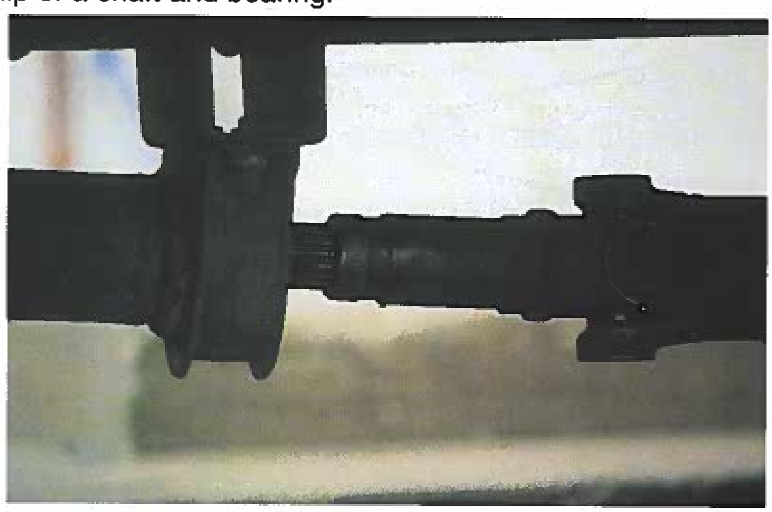
Because the shaft is a solid piece of metal, it is not easily bent. If the shaft is bent, it cannot accurately transfer mechanical energy. In cases where flexibility is needed, ***universal joints*** are placed on the ends of the shaft. **Figure 9-25** is an illustration of a common universal joint. Universal joints allow connected shafts to spin freely, while permitting a change in direction.

Shaft: A long, cylindrical piece of metal used to transfer mechanical energy in many types of machines.

Bearing: A specially shaped piece of metal used to support shafts and reduce friction between metal parts as they move past or revolve around each other.

Universal joint: A joint that allows connected shafts to spin freely, while permitting a change in direction.

Figure 9-23. The drive shaft of a rear-wheel drive car shows the normal relationship of a shaft and bearing.



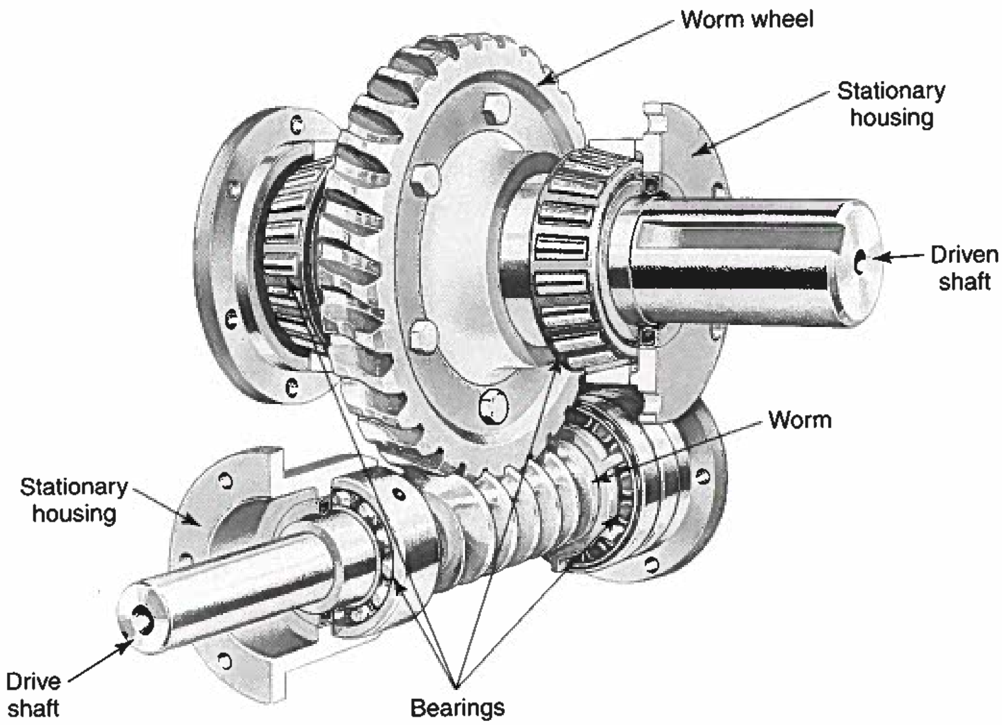
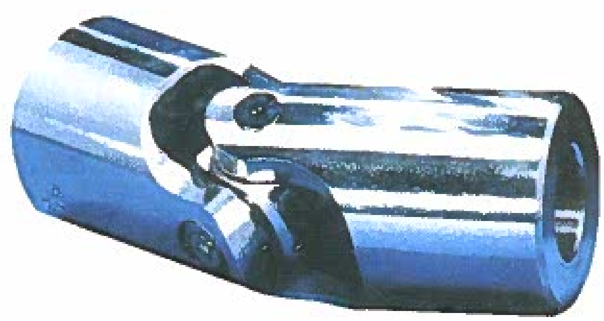


Figure 9-24. The shafts in this assembly are supported in their housings by bearings. The bearings reduce friction between the rotating and stationary parts. The worm gear, comprised of a worm and a worm wheel, transmits power between drive and driven shafts. (Cleveland Gear)

Mechanical Advantage

Mechanical advantage is increased force, speed, or distance and the benefits of that increase created by using a machine to transmit force. The force you apply to a machine is actually multiplied. For example, imagine trying to move a large rock that is partially embedded in the ground with only your arms, legs, and body weight. The task seems extremely difficult, if not impossible. If you use a long metal bar as a lever in combination with your physical effort, you increase the amount of force produced. The increase in force is a gain in mechanical advantage.

Figure 9-25. A universal joint is often placed between two shafts not on the same plane. It allows the two shafts to turn together without binding or breaking. (Boston Gear)



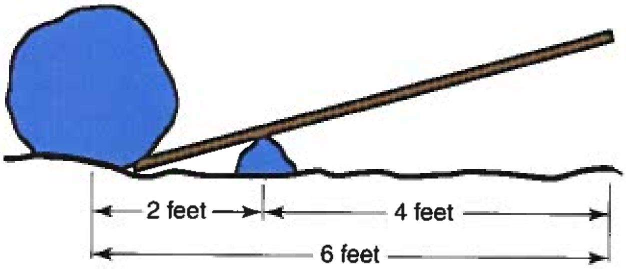
This advantage can be calculated by dividing the input distance by the output distance. For example, suppose you are using the metal bar wedged between two rocks. See **Figure 9-26.** You exert force 4′ away from the smaller rock. The smaller rock is the fulcrum, or pivot point. The load is 2′ away from the fulcrum. This means the machine provides twice the force you put into it. Using mechanical advantage usually results in less effort required to perform a task than if a mechanical device was not used.

Mechanical advantage: An increased force and the benefits of that increase created by using a machine to transmit force.

Using Simple Machines to Gain Mechanical Advantage

Simple machines can make lifting and other strenuous activities easier by multiplying force. They cannot, however, produce more actual power than the power put into them. These machines simply modify the

Figure 9-26. Levers give their users a mechanical advantage. Less energy is required than if trying to move the load by lifting it.



characteristics of the power provided in order to achieve a specific goal, such as making lifting easier. There is a trade-off when using simple machines. The trade-off for gaining force is a loss of speed or distance.

This trade-off is true for all advantage-gaining devices, including those associated with other forms of power, like fluidics and electricity. If effort is made easier, rate will be sacrificed. An example is the transmission in an automobile. If the car is stopped at a traffic light and the light turns green, torque is required to get the vehicle moving, not speed. A low gear produces that torque, but it will not get the car moving very fast. Once the car is moving, the transmission is shifted into mid-range gears that provide less torque and allow for more speed. If driving on a highway, the car may be shifted into a high gear, such as fourth or fifth gear. These higher gears provide much higher speeds, but much less torque. To climb a steep hill, it may be necessary to shift into a lower gear to provide more torque. Today, many modern automobiles use an automatic transmission. This type of transmission has the ability to sense strain on the engine and shift the transmission into the appropriate gear range automatically to meet the power characteristics required for the terrain (more speed or more torque).

Levers

We can change the force produced by first-class levers by changing the fulcrum's position between the input force and the load. If the fulcrum is closer to the load, the force is increased. When the fulcrum is exactly centered between the two, the force on both the load and the input force are equal. As the fulcrum moves toward the input force, the machine loses strength, but the distance we can move the load increases. Rowing teams use this positioning to increase the distance their oars move through the water. See **Figure 9-27.**

Figure 9-27. Levers in use. A—Oars are based on the principle of first-class levers. They are designed to be distance multipliers. (Harvard University) B—Are these paddles examples of a first-class lever or a third-class lever?

A

B

Pulleys

Pulley systems provide a mechanical advantage. For example, in a pulley system that uses four pulleys, a 4:1 mechanical advantage is produced. This means that every 25 lbs. of input force results in about 100 lbs. of lifting, or output force. The trade-off, however, is that 4′ of rope must be reeled in to create just 1′ of lift on the output side of the system. The distance between the fulcrum and input force is larger on a moveable pulley system. This is why it has greater mechanical advantage in force than a fixed pulley system.

Wheels and axles

The wheel and axle is a simple machine consisting of two parts. The larger circular part is called the wheel, and the smaller circular part is called the axle. Practical examples of the wheel and axle at work include large crank handles. **Figure 9-28** shows a crank handle that can help to generate a large mechanical advantage. Such crank handles are often used on retractable boat lifts. Through a cable system, a small boat can actually be lifted right out of the water.

Inclined planes

Using a ramp makes it easier to load packages onto a loading dock. The distance that must be covered is much greater, however, than if the load could simply be lifted directly onto the loading dock. Using a ramp makes loading easier, but more time-consuming, because of the increased distance that must be covered to reach the desired height.

Wedges

If you calculate the mechanical advantages of different-shaped wedges, you find that the longer the wedge (compared to thickness), the greater the advantage. See **Figure 9-29.** This is the reason you can split logs easier with thinner wedges.

Gears

Gears are often used to modify the characteristics of mechanical power and not always used to gain torque. **Figure 9-30** presents a diagram of an automobile engine coupled to a manual transmission. A belt or chain may be

Figure 9-28. Calculating mechanical advantage with a wheel and axle is actually easy. If the diameter of the axle is 3″ and the diameter of the wheel is 4′, the mechanical advantage can be calculated as follows: 4′/.25′ = 16:1 mechanical advantage. This means that if the wheel is driving the axle, it will convert every pound of effort on the handle into 16 lbs. of force at the axle. On the other hand, if the axle is driving the wheel, every inch the axle moves, the wheel will move 16″.

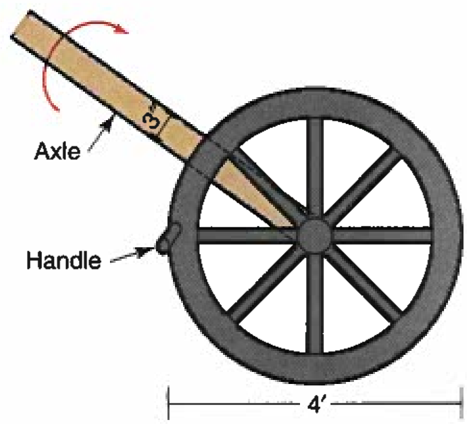


Figure 9-29. A long, thin wedge has more mechanical advantage than a short, fat one.

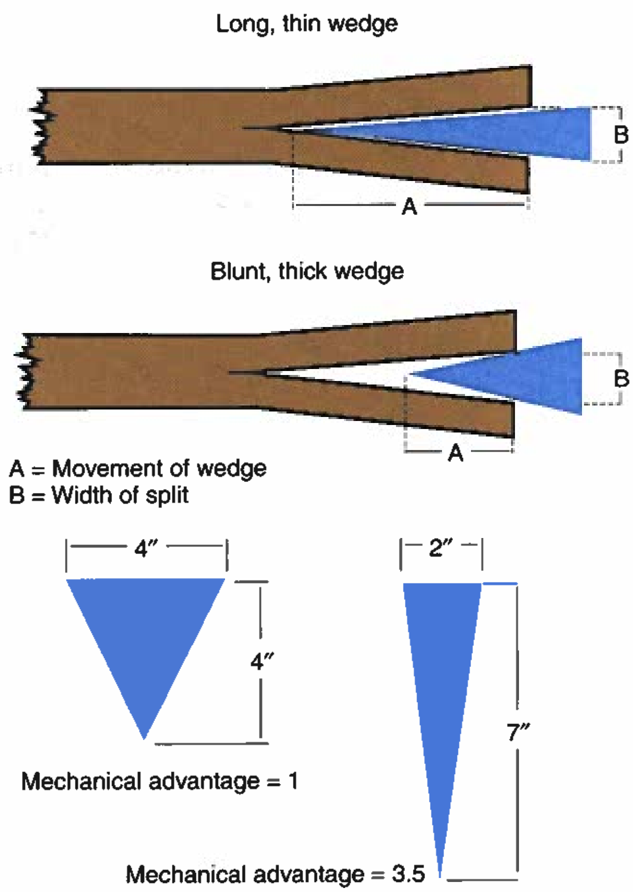
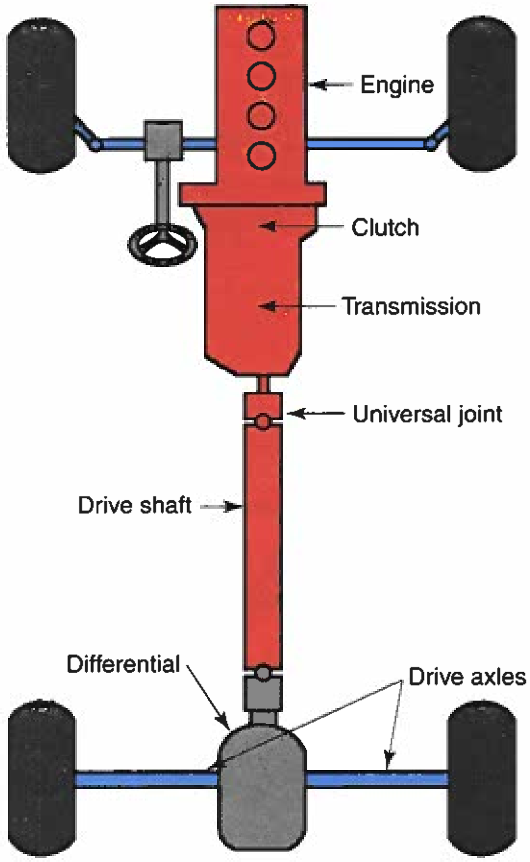


Figure 9-30. A transmission modifies the characteristics of the automobile's engine power, changing speed and torque.



used to span the distance between two gears, but the number of teeth on the two gears determines the mechanical advantage produced by the gear set. See **Figure 9-31.** For example, a machine is chain driven by a motor that rotates at 1750 rpm. Attached to the motor is a 50-tooth drive gear. The machine is designed to rotate at a speed of 2500 rpm. How many teeth must the driven gear have? See **Figure 9-32.**

A simple gear train may be created using three or more gears. When three or more gears are used, the gears between the driver gear and the driven gear are referred to as ***intermediate gears***. They are also sometimes called ***idler gears***. See **Figure 9-33.** The idler gear is often used in the middle of a gear set to change the rotation of the driven gear to spin in the same direction as the driver gear. Note that, no matter how many idler gears are used between the driver gear and the driven gears, none of them has any effect on the mechanical advantage of the gear train. The impact is based on the relationship of the driver gear to the driven gear.

Gears arranged in a series gear train provide only limited mechanical advantage. When gears are arranged in a compound gear

Intermediate gear: A gear between a driver gear and a driven gear.

Idler gear: See *Intermediate gear*.

Figure 9-31. Different combinations of gears modify the characteristics of power from a motor or other power source.

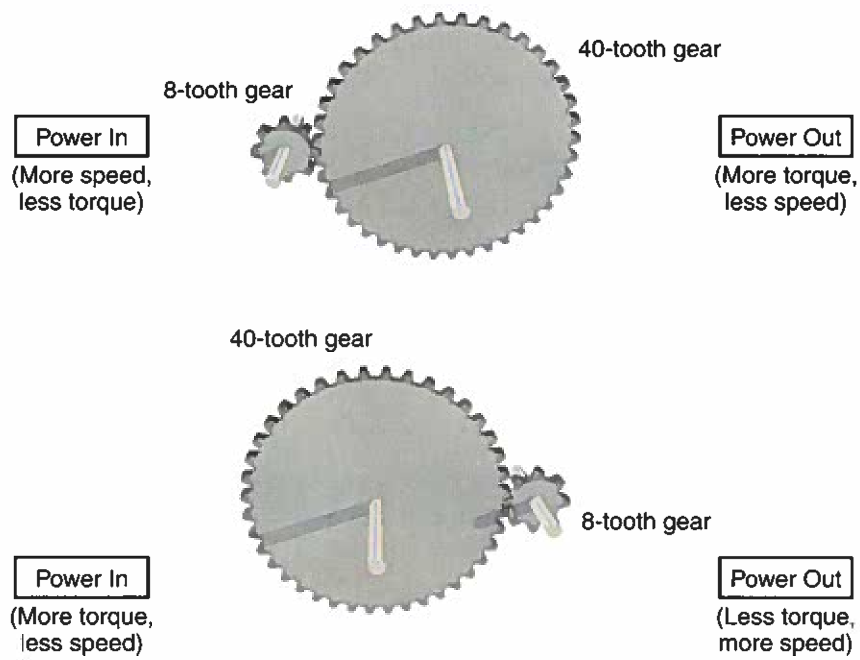
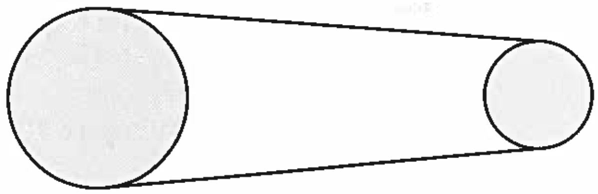
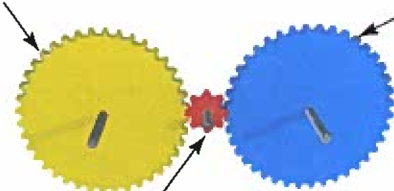


Figure 9-32. Calculating the mechanical advantage of a gear set. In this example, torque is actually sacrificed in order to make the machine spin the proper revolutions per minute (rpm). The mechanical advantage is in terms of speed, in this instance, instead of torque, as is usually the case when mechanical advantage is discussed.



1. 1750 rpm × 50 teeth = 87,500
2. $\frac{87{,}500}{2{,}500 \text{ rpm}}$ = 35 teeth
3. $\frac{50}{35}$ =1.43 mechanical advantage of speed

Figure 9-33. A gear train consists of the drive gear, one or more idler gears, and the driven gear. Idler gears do not alter mechanical advantage.



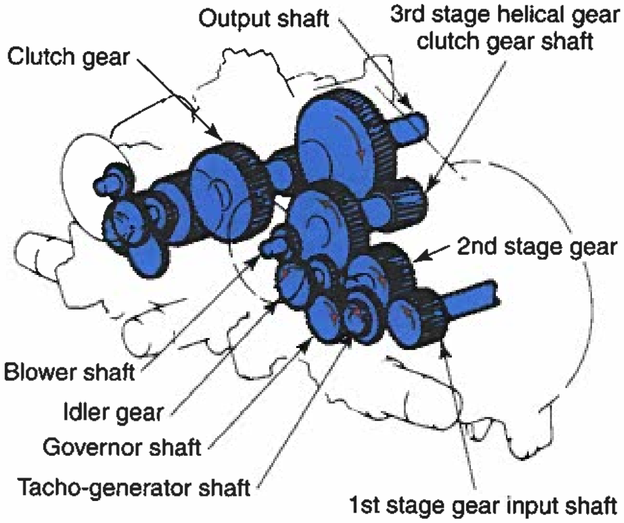
cluster along parallel shafts, however, force is greatly multiplied and creates much greater mechanical advantage. A ***compound gear cluster*** consists of more than two gears arranged in such a way as to gain significant mechanical advantage of force or speed. See **Figure 9-34.** Gear boxes often use compound gear clusters in order to generate much greater mechanical advantages than could be created by a two-gear set. When the technique of compound gearing is utilized in conjunction with specialty gears, such as a worm gear, tremendous mechanical advantages can be created.

Compound gear cluster: More than two gears arranged in such a way as to gain significant mechanical advantage of force or speed.

Calculating the Mechanical Advantage of Compound Machines

A compound machine employs two or more simple machines. We can determine the mechanical advantage of a compound machine. To do so, complete the following steps:

Figure 9-34. Compound gear clusters are used to increase mechanical advantage. This is the reduction gearbox used in the power system of a helicopter. (Bell Helicopter Textron)



1. Identify each of the simple machines contained within the compound machine.
2. Calculate the mechanical advantage of each simple machine.
3. Multiply the mechanical advantages of each simple machine together. The product of this calculation is the total mechanical advantage for the compound machine, as demonstrated in **Figure 9-35.**

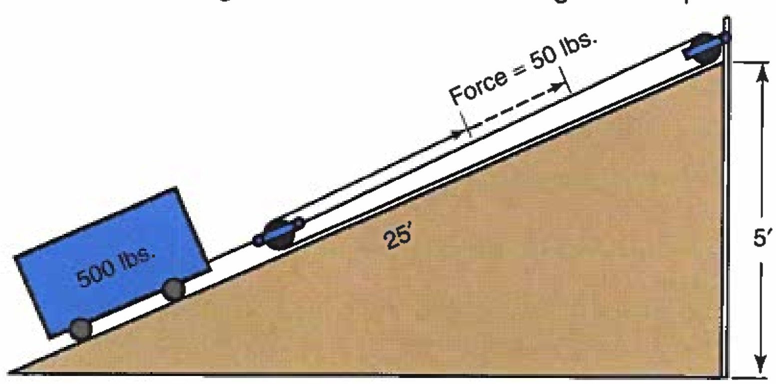
Ideal Mechanical Advantage (IMA) vs. Actual Mechanical Advantage (AMA)

Ideal mechanical advantage (IMA) is a ratio of the forces or the distances involved in a mechanism. In the real world, however, we must account for the amount of energy lost through friction. Friction is the heat energy that is a common by-product of mechanical energy. ***Actual mechanical advantage (AMA)*** is the ratio of the increase of force or effort by a machine, including energy lost through friction. AMA is always less than IMA because IMA assumes 100% efficiency, and AMA accounts for frictional losses.

Ideal mechanical advantage (IMA): A ratio of the forces or the distances involved in a mechanism. It assumes 100% efficiency.

Actual mechanical advantage (AMA): The ratio of the increase of force or effort by a machine, including energy lost through friction.

Figure 9-35. Calculating the mechanical advantage of compound machines.



Inclined Plane and Pulleys

Mechanical advantage of inclined plane = 25′:5′
= 5:1

Mechanical advantage of pulley system = 2:1

Mechanical advantage of compound machine = 5:1 × 2:1
= 10:1

Force on rope needed to move load = Load ÷ Mechanical advantage

$= 500 \text{ lbs.} \div \frac{10}{1}$

= 50 lbs.

To calculate AMA, a formula that involves the forces in the system must be used. The force is often measured in pounds of weight. In order to determine the total effort in the system, force is multiplied by the distance of the lever on the input side of the fulcrum. Divide the output effort by the input effort to find AMA.

All the mechanical advantage calculations we have done in this chapter are really IMA calculations. We have not taken any frictional loss into account. When we do live measurements to determine mechanical advantage, sometimes the numbers do not work exactly because of frictional loss in the real world. For instance, let us say a pulley system is supposed to provide a 4:1 mechanical advantage. In theory, only a little more than 25 pounds should lift 100 pounds. In reality, you may find that 28 pounds are required.

The efficiency of machines is a comparison of the input effort to the amount of output effort. One way to calculate efficiency (as a percentage) is to divide AMA by IMA and multiply the answer by 100.

$$\frac{100 \text{ lbs.}}{28 \text{ lbs.}} = 3.57 \text{ AMA} \qquad \frac{100 \text{ lbs.}}{25 \text{ lbs.}} = 4.0 \text{ IMA} \qquad \frac{3.57 \text{ AMA}}{4.0 \text{ IMA}} \times 100 = 89\% \text{ efficient}$$

This simple calculation can determine both system efficiency and percentage of effort lost as a result of friction. See **Figure 9-36.**

Figure 9-36. Calculating the efficiency of a mechanical system.

$$\%E = \frac{\text{AMA}}{\text{IMA}} \times 100$$

Career Skills

Ethical Behavior

Ethical behavior on the job means conforming to accepted standards of fairness and good conduct. It is based on a person's sense of what is right to do. Individuals and society as a whole regard ethical behavior as highly important. Integrity, confidentiality, and honesty are crucial aspects of ethical workplace behavior. Integrity is firmly following your moral beliefs.

Unfortunately, employee theft is a major problem at some companies. The theft can range from carrying office supplies home to stealing money or expensive equipment. Company policies are in place to address these concerns. In cases of criminal or serious behavior, people may lose their jobs. If proven, the charge of criminal behavior stays on the employee's record. Such an employee will have a difficult time finding another job.

Summary

Mechanical power systems control mechanical energy to do work. They consist of machines that can change size, direction, and speed of forces, as well as change the type of motion. The three types of motion studied in transportation technology are reciprocating, rotary, and linear.

There are six simple machines used to control mechanical energy: the lever, the pulley, the wheel and axle, the inclined plane, the screw, and the wedge. All six rely on the principle of either the lever or the inclined plane. Mechanical power systems move mechanical energy through special transmission devices. These devices include clutches, pulleys and belts, chains and sprockets, and shafts and bearings.

Mechanical advantage is the increase in force a machine provides. Ideal mechanical advantage (IMA) is the ratio of forces assuming the mechanism is 100% efficient. Actual mechanical advantage (AMA) considers energy loss due to friction.

Key Words

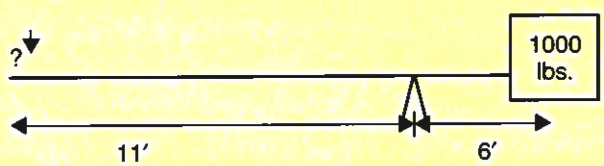
All the following words have been used in this chapter. Do you know their meanings?

actual mechanical advantage (AMA)
bearing
brake horsepower (bhp)
clutch
complex machine
compound gear cluster
displacement
first-class lever
frictional horsepower (fhp)
fulcrum
gear
ideal mechanical advantage (IMA)
idler gear
inclined plane
indicated horsepower (ihp)
intermediate gear
lever
mechanical advantage
Prony brake
pulley
scalar quantity
screw
second-class lever
shaft
simple machine
third-class lever
universal joint
vector quantity
velocity
wedge
wheel and axle

Test Your Knowledge

Write your answers on a separate sheet of paper. Do not write in this book.

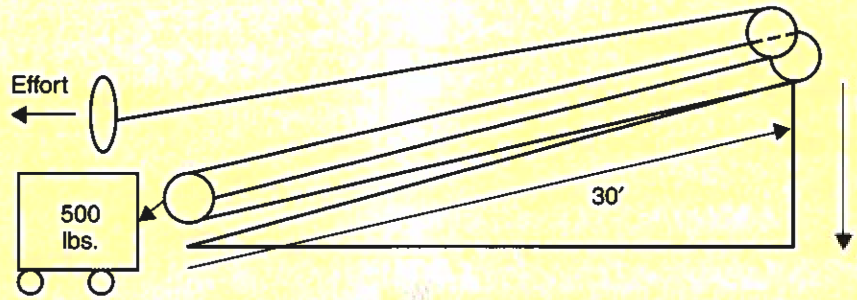
1. Machines can change the _____, _____, and _____ of forces.
2. The six simple machines are _____, _____, _____, _____, _____, and _____.
3. A wheelbarrow is an example of a(n) _____ lever.
4. Explain the differences among first-, second-, and third-class levers.
5. Third-class levers always increase the _____ of the load.
6. Shovels and baseball bats are examples of _____ levers.
7. In what ways do single fixed and single moveable pulleys differ?
8. Screws and wedges operate on the principle of the _____.
9. Name three types of gears and state a common application for each.
10. Identify the two primary characteristics of power.
11. How much torque is required to drive a pump rated at 60 horsepower (hp) that must operate at a speed of 350 revolutions per minute (rpm)?
12. Summarize the difference between scalar and vector quantities.
13. How much force would it take to stabilize the following load?



14. A(n) _____ is the device that links the power system to the drive system in many vehicles.
15. List the five ways that pulley and belt systems control mechanical energy.
16. A mechanical system that provides _____ means that the power-transmitting device will not slip when used.
17. _____ are used on the ends of shafts at points where flexibility is needed.
18. A motor spins at 3550 rpm and is connected to a 4″ diameter pulley. This pulley feeds a 20″ diameter pulley that drives an auger blade for digging holes in the ground. What is the mechanical advantage that the pulleys create?
19. Do gears significantly change the amount of power produced by a motor or engine? Explain your answer.
20. When using a pulley system, you determine that you must reel in about 6′ of rope in order for the load to be elevated by only 1′. Based on this information, what is the approximate mechanical advantage of the pulley system?
21. The drive gear on a motor has 36 teeth and revolves at a speed of 1150 rpm. How many teeth must the driven gear have if it must rotate at 575 rpm?

22. The rotating portion of a conveyor drive system spins at 80 rpm and is driven by a gear containing 100 teeth. If the drive gear on the motor has 20 teeth, what is the speed of the motor?

23. Calculate the mechanical advantage of the following compound machine.



For questions 24–28, match the term in the left-hand column with the correct definition in the right-hand column.

24. _____ Complex machine.
25. _____ Fulcrum.
26. _____ Velocity.
27. _____ Mechanical advantage.
28. _____ Actual mechanical advantage (AMA).

A. An increase in force provided by a machine.
B. A ratio that includes energy loss in a mechanical system.
C. A measurement that includes speed and direction.
D. Made up of many simple machines.
E. The point around which a lever rotates.

29. A pulley system develops a 6:1 ideal mechanical advantage (IMA), but you measure the AMA at only 5.75:1. What percentage of loss has occurred due to friction?

STEM Activities

1. Survey the lab area in your classroom and list the various types of equipment contained. Compile one master class list of equipment and determine the simple machines found in each piece of equipment.
2. Design and explain the operation of a useful, compound machine that combines two or more simple machines to perform the following tasks:
   A. Lifting a boat out of the water.
   B. Steering a go-cart.
   C. Raising a ladder.
3. Use LEGO® toys or a similar mechanism kit to design and build the following:
   A. A slow car. Design a car that goes as slow as possible from the starting point. You must use only parts within your kit, and the car must make forward progress.
   B. A "lift-a-lot." Design a lifting device that can lift the most weight.
   C. A clean sweeper. Design a device to pick up small balls of paper from a tabletop and deposit them in a bin that can be emptied.