

**EVALUATING
ACADEMIC READINESS
FOR APPRENTICESHIP TRAINING**
Revised for
ACCESS TO APPRENTICESHIP

**SCIENCE SKILLS
SIMPLE MACHINES AND MECHANICAL ADVANTAGE**

**AN ACADEMIC SKILLS MANUAL
for
The Precision Machining And Tooling Trades**

This trade group includes the following trades:
General Machinist, Tool & Die Maker,
Mould Maker, Pattern Maker, and
Machine-Tool Builder Integrator

*Workplace Support Services Branch
Ontario Ministry of Training, Colleges and Universities*

Revised 2011

In preparing these Academic Skills Manuals we have used passages, diagrams and questions similar to those an apprentice might find in a text, guide or trade manual.

This trade related material is not intended to instruct you in your trade. It is used only to demonstrate how understanding an academic skill will help you find and use the information you need.

SCIENCE SKILLS

SIMPLE MACHINES AND MECHANICAL ADVANTAGE

*An academic skill required for the study of the
Precision Machining and Tooling Trades*

INTRODUCTION

People have always used whatever tools they could find or invent to help make life easier. Simple machines such as a lever increase the force available to move a heavy object. In your work, you have to lift and carry heavy objects. Simple machines make work easier by providing extra force in situations where human muscle power is not enough. The increase in force provided by a machine is called a mechanical advantage.

The main types of simple machines are:

- ◆ the lever, from which the pulley, the wheel and the axle developed,
- ◆ the inclined plane, from which the screw and the wedge developed.

These simple machines have been put together in various ways to create more complex machines. When complex machines are harnessed to a source of power such as gasoline or electricity, they transform energy from one form to another. The machining and tooling trades rely on machines that convert electrical energy to mechanical energy in order to perform many complicated tasks.

This skills manual looks at simple machines and the mechanical advantage gained by using a machine, including:

- ◆ Definitions of work and power
- ◆ Different ways machines increase force
- ◆ How a simple machine works
- ◆ The lever
- ◆ The wheel and axle
- ◆ Torque
- ◆ Gears
- ◆ The pulley
- ◆ The inclined plane
- ◆ Actual and ideal mechanical advantage

WORK AND POWER

We all have a pretty good idea of what doing work means in our everyday life. Work also has a scientific definition. At the mechanical level, **work** is done when a force acts on an object and causes it to be moved. For example, work is done when you remove a broken screw because you move the screw from one position to another.

To find the work done in moving an object, the force applied is multiplied by the distance the object is moved. This can be stated:

$$\text{Work} = \text{force} \times \text{distance}$$

The metric unit of work is the joule. A **joule** is the work done when a force of 1 newton acts on an object over a distance of 1 meter. You do 1 joule of work when you push, pull, carry or lift a stationary mass of 1 kg over a distance of 1 meter.

The imperial unit of work is the foot-pound. A **foot-pound** is the amount of work done by moving a one pound object over a distance of 1 foot.

Power is the rate of doing work. It indicates how long it takes to do the job. In order to judge the effectiveness of a machine, the rate at which it works is an important consideration. Power is the work done divided by the amount of time taken to do it.

$$\text{Power} = \text{work} / \text{time}$$

The metric unit of power is the **watt** (w) and the imperial unit is the **horsepower** (hp).

DIFFERENT WAYS MACHINES INCREASE FORCE

Machines do not create energy so they will not work by themselves. They need an initial force such as the pull of gravity, the push of our muscles or the turning of a switch. Then the machines can change the force so that we have the right amount of force in the right place. Here are some ways that machines can change a force:

1. **Machines can transform energy from one form to another.** When the voltage from an arc welder melts the metal wire, electrical energy is changed to heat energy. A power saw converts electrical energy to mechanical energy used to cut a sheet of metal.
2. **Machines can transfer energy from one place to another.** Connecting rods, crankshafts, drive shafts and axles are machines that transfer energy from the cylinder of an engine to the wheels. They also change linear movement into circular movement and vice-versa.
3. **Machines can multiply force, as when a hydraulic lift increases the weight that can be lifted.** A machine such as a hydraulic lift uses the pressure of a fluid to increase the amount of force available.
4. **Machines can multiply speed.** We can move a heavy load faster by pushing it in a wheeled cart than by pushing it along the floor.

HOW A SIMPLE MACHINE WORKS

When an object is lifted, a force must be applied to overcome its weight.

- ◆ *The force used to move an object is called the **applied or effort force**.*
 - The terms applied force and effort force are used interchangeably,
- ◆ *An object's opposition to being moved is called the **resistance force or the load**.*
 - The terms load and resistance force can also be used interchangeably.
- ◆ If friction is ignored, an object's resistance to being moved is generally the same as its weight, so the load is considered to be the same as the object's weight.

A simple machine uses a single applied force to do work on a single load. A single **effort force** applied at the end of a crowbar will pry out a nail, which is the **load force**. When a simple machine does work, both the effort force (the crowbar) and the load (the nail) move a certain distance. So work is done where the effort force is applied and where the load is moved. Here are some examples:

- You use a lever to get a large block out of the way.
 - Work done on the long arm of a lever, at the point where your muscles apply a force by pushing down, causes the lever to move.
 - Work done by the lever where the shorter arm of the lever moves up, causes the load or stone to also move.
 - This results in the block moving.
- The crowbar, a simple machine, enables you to remove a nail that you couldn't pull out with your fingers: When you use the crowbar, here is what happens:
 - The effort, or applied, force occurs in your arm and the shaft of the crowbar, up to where it bends.
 - The resistance force or the load occurs in the crowbar, after the bend, and the nail.
 - When you pry the nail out, you move the effort force (your arm and crowbar shaft) a certain distance.
 - The resistance force, or load, (the crowbar end and the nail) also move when you press on the crowbar, although they move a shorter distance.
 - The short amount the nail moves is enough to result in pulling it out of the board.

The work done to move the load – the stone or the nail - is the same as the work supplied by the effort force - the crowbar and your arm. This is expressed by saying the output (the work done on the load) is the same as the input (the applied force).

THE LEVER

*A **lever** is a rigid bar which is free to turn about a pivot point called the **fulcrum**.*

- The side of the lever that you push down on is called the **effort arm**.
- The arm on the other side of the fulcrum that goes under the load is called the **resistance (or load) arm**.

Levers enable you to move objects (resistance forces or loads) that are too heavy to push or lift. They do this by acting over a longer distance than our arms can.

If you want to move a heavy object like a stone, you can get a long bar, put the fulcrum close to the stone and pry it up. You can see in **Figure 1** that when you push down on your end of the lever, the load will be lifted up. The effort force you need to make this happen will be less than the effort you would need to lift the load with your arms.

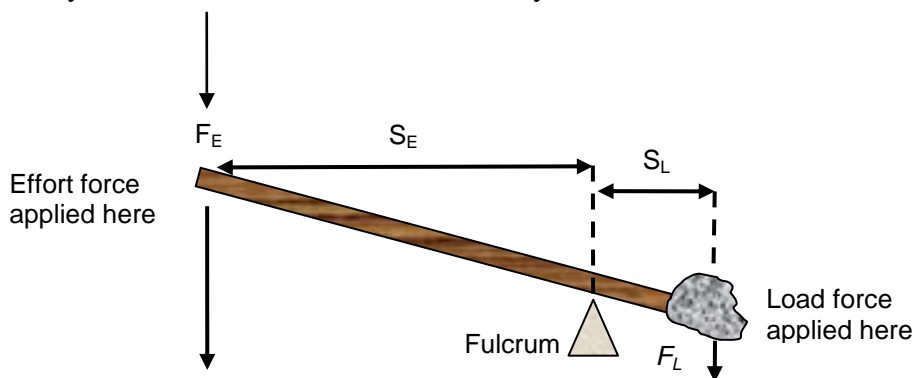


FIGURE 1: Work Done By a Lever

A large load is placed a short distance from the fulcrum (S_L) on one end of the lever. It can be moved by a weaker force on the other end of the lever if the effort force is a longer distance (S_E) from the fulcrum.

The lever does work on both sides of the fulcrum.

- The length and the force on *each side* of the fulcrum are multiplied together to determine the amount of work done on each side.
- The position of the fulcrum determines the length that each force moves through.
- The load force is the weight of the block.
- The effort force comes from your arms pushing on the effort side of the lever.

When you push on the lever and make it move, the work done on both sides is the same. Work output is equal to the work input. This can be represented by the equation:

$$F_E \times S_E = F_L \times S_L$$

where:

F_E is the effort force

S_E is the distance of the effort force to the fulcrum

F_L is the resistance force or load

S_L is the distance of the resistance force to the fulcrum

The distances used in the equation are those of the length of the lever on each side of the fulcrum (Look again at Figure 1).

When work is done, those lengths are proportional to the distance each end of the lever arcs through as the effort force is applied.

Example: The length of lever like the one in the diagram is 60 inches on one side of the fulcrum and 12 inches on the other. If the long end of the lever moves 20 inches, how far does the shorter end move?

Since the lengths on each side are proportional, we can write them as ratios or fractions on different sides of an equal sign. We will write the unknown length of the shorter end of the lever as D .

$$\frac{D}{12} = \frac{20}{60}$$

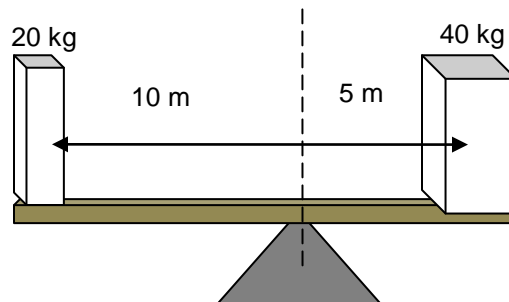
$$D = \frac{20 \times 12}{60}$$

$$= 4$$

The length that the shorter end of the lever moves is 4 inches.

As the end of the lever under the stone is moved 4 inches, it in turn moves the stone. Our job is successful as the stone is moved out of the way.

Example: A load of 20 newtons (n) on one end of a lever that is 10 meters from the fulcrum will balance a second load of 40 newtons placed 5 meters from the fulcrum.



$$20 \text{ n} \times 10 \text{ m} = 40 \text{ n} \times 5 \text{ m}$$
$$200 \text{ n m} = 200 \text{ n m}$$

The lever is in equilibrium with both sides balancing each other.

Next we will look at an example of how to find the effort force needed to move a load:

Question: You need to move a 400 pound block with a 6 foot lever. The 400 pound load force is positioned at the end of the lever 1 foot away from the fulcrum. You will apply the effort force at the other end of the lever, 5 feet from the fulcrum. What effort force will you need?

$$F_E \times S_E = F_{Ll} \times S_L$$

$$\begin{aligned}F_E &= \text{effort force} \\S_E &= 5 \text{ ft} \\F_L &= 400 \text{ lb} \\S_L &= 1 \text{ ft}\end{aligned}$$

$$F_E \times 5 \text{ ft} = 400 \text{ lb} \times 1 \text{ ft}$$

$$F_E = \frac{400 \times 1}{5}$$

$$F_E = 80$$

The resistance force of 400 lb is balanced by an effort force of 80 pounds 5 feet from the fulcrum.

Question: What if you aren't strong enough to move a load of 80 lbs with a lever that is 5 feet from the fulcrum? If you increase the length of the lever so that the effort distance (S_E) is longer, you will need less effort force to move the load. You can increase the mechanical advantage of the lever by making your side longer, say to 10 feet instead of 5.

To balance the effect on both sides of the equation, it now is:

$$F_E \times S_E = F_L \times S_L$$

$$\begin{aligned}F_E &= \text{effort force} \\S_E &= 10 \text{ ft} \\F_L &= 400 \text{ lb} \\S_L &= 1 \text{ ft}\end{aligned}$$

$$F_E \times 10 \text{ ft} = 400 \text{ lb} \times 1 \text{ ft}$$

$$F_E = \frac{400 \times 1}{10}$$

$$F_E = 40$$

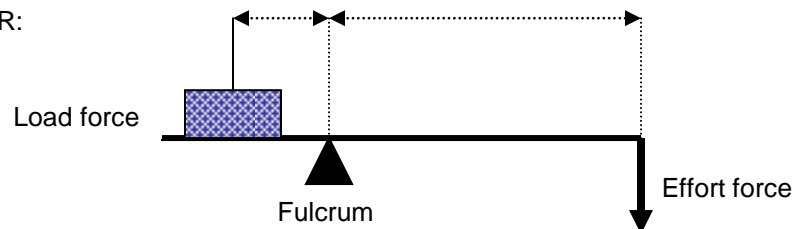
F_E is now only 40 lb. A push of just 40 lbs on your side of the lever at 10 ft from the fulcrum will move the load.

To move a load using a lever, the longer the distance from the fulcrum to the point where the effort force is applied, the less effort force is needed to move the load. The length of the lever gives us a mechanical advantage in that we can move the block using less force.

Types of Levers

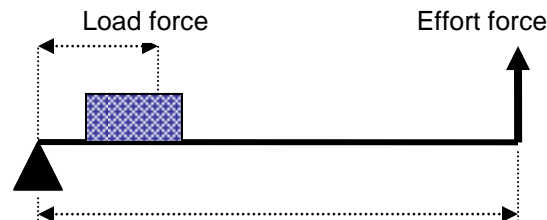
In a lever like the one in Figure 1, the fulcrum is placed between the applied force and the load. In other types of levers, the fulcrum can be at one end. The applied force and the load can also be in different positions on the lever. Levers are classified as first, second or third class based on where the effort and resistance forces are positioned relative to the fulcrum. See Figure 2.

FIRST CLASS LEVER:
Example - nail puller



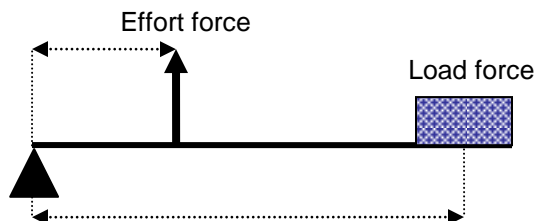
In a first class lever the load force and the effort force are on opposite sides of the fulcrum

SECOND CLASS LEVER:
Example – wheel barrow



In a second class lever the load force and the effort force are on the same side of the fulcrum, with the fulcrum at one end, the load in the middle and the effort applied at the other end

THIRD CLASS LEVER:
Example - hammer



In a third class lever the load force and the effort force are on the same side, with the fulcrum at one end, the effort applied in the middle and the load at the other end

FIGURE 2: Types of Levers

*In a **first class lever**, the fulcrum is between the load at one end and the effort force which is applied at the other end of the lever. This is what is typically thought of as a lever.*

First class levers include

- scissors,
- balance scales,
- nail pullers,
- and pliers.

Most jacks are first class levers. The resistance force or load is at one end supported by the jack. The fulcrum is between the load and the pump handle. The pump handle is at opposite end of the lever from the load. In a jack, there is often a hydraulic cylinder as part of the fulcrum to assist in the lifting.

A second class lever has the fulcrum at one end, the weight balanced in the middle and the effort applied at the other end. A wheelbarrow is a second class lever. The wheel is the fulcrum (the load pivots on the axle of the wheel) and the effort is applied at the handles at the other end from the wheel. The weight or resistance of the load is between the fulcrum and the handles. Other second class levers include:

- bottle openers
- and nutcrackers.

A third class lever has the fulcrum at one end, the load at the other end and the effort force between them. An example of a third class lever is a hammer. The fulcrum is the elbow or wrist, the hammer head is the effort and the load is the resistance of the wood to the nail. Other examples of third class levers are:

- fishing rods
- and tweezers.

THE WHEEL AND AXLE

A *wheel and axle* uses the principle of a lever to give a mechanical advantage.

- A wheel is basically a lever where the larger wheel, actually the edge of the main wheel, rotates around the smaller wheel of the axle.
- The smaller wheel of the axle rotates around the fulcrum at the center.
- The effort force is applied in a circular direction around the fulcrum to turn the axle. This circular, turning force is called *torque*.
- Since the axle is connected to the main wheel (or tire rim), both turn together.
- There is usually a fair distance between the outside of the wheel and the outside of the axle, so a wheel provides a significant mechanical advantage.

In a vehicle, the wheel can transmit energy from the engine. When an engine transmits a rotary force to the axle, the axle causes the wheels to turn. The force applied to the axle and transmitted to the wheels results in the motion of the car. A force such as the rotation of a wheel that results in a turning motion is called torque.

TORQUE

Torque refers to a force that produces a turning motion in an object such as a wheel, a gear or a bolt and wrench. A torque causes the shaft of the object to rotate around an axis or a pivot point. When you turn a wrench that pivots on a bolt, you apply a torque or a turning force to the bolt that causes it to be loosened or tightened.

Using a Wrench to Produce Torque

When you want to loosen or tighten a bolt, you use the force of your muscles at one end of a wrench to rotate that end. The head of the wrench is connected to the bolt at the pivot end. This part of the shaft also turns, causing the bolt to rotate. The length of the wrench is measured from the center of the bolt to the end where the force is applied.

The torque applied by the wrench to turn the bolt depends on the amount of force applied and the length of the wrench. So torque is calculated by multiplying the force times the length of the wrench. Torque is measured in the unit *pound foot* in the imperial system and *meter newton* in the metric system.

To get enough rotation or torque to loosen a bolt with a wrench of a given length, you need to apply a certain amount of force. If you use a **longer** wrench, you can apply **less** force. If you use a **shorter** wrench, you will need to apply **more** force. See Figure 3.

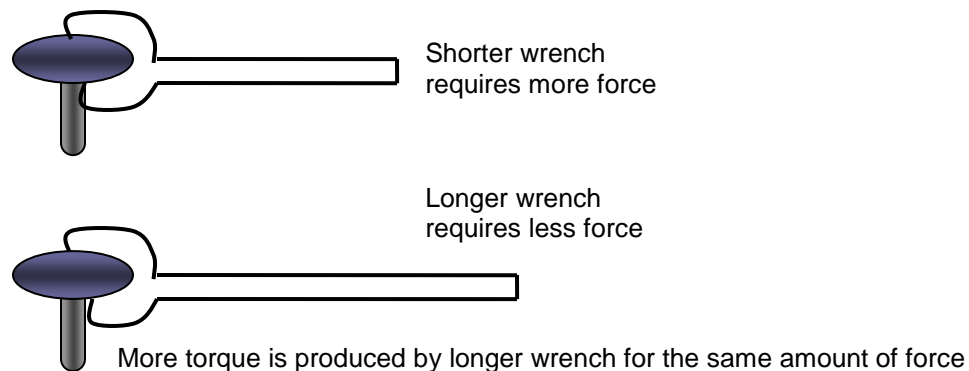


FIGURE 3: Amount Of Torque Increases With Size Of Wrench

If you tried to loosen a bolt with a 15 cm wrench but found the bolt was on too tightly, what size wrench should you try next – 10 cm or 25 cm?

If you picked the 25 cm one, you have a good chance of being successful. This is because less force is required to produce the same amount of torque as the distance from the center increases. A longer wrench turned with the same amount of force (exerted by the pulling with your muscles) will give you more torque or ability to make the bolt turn.

A wrench gives you a mechanical advantage over using your fingers to loosen a bolt because it acts as a lever. A lever increases the distance over which the force acts compared to your fingers. Since the force is multiplied by the distance it is applied over, the longer the distance, the more torque there is for the same amount of applied force.

GEARS

Gears are an important part of complex machines. Most mechanical devices include gears of one type or another that serve various, essential functions. Gears are used in pairs or combinations to:

- ◆ transmit motion,
- ◆ change direction of motion,
- ◆ increase or decrease speed,
- ◆ transmit power from one part of a machine to another.

Gears are made on special gear-cutting machines, each one designed for a different type of gear.

Spur Gears

The most widely used gear is the spur gear. A spur gear is a wheel or cylinder with teeth cut into the outside circumference parallel with the axis of rotation. Pairs of spur gears are used to transmit motion between parallel shafts.

- ◆ When two spur gears are used together, the teeth of one gear fit between the teeth of the other. We say the precisely fitting teeth of the two gears are meshed. When two spur gears are meshed together, the larger of the two is called the gear and the smaller one is called the pinion.
- ◆ If two gears with precisely fitting teeth are placed in contact and one of the gears is rotated, the other gear will also rotate. The teeth of the first gear are meshed with the teeth of the second gear. As the teeth of the first gear turn, they push against the teeth on the other gear and cause it to rotate also.
- ◆ The gear that causes the second gear to turn is called the driver. Either the larger or the smaller gear could be the driver. As the driver turns, its teeth mesh with the teeth of the second gear. The rotation of the driven gear transfers motion to its shaft.

The following shows the gear and pinion of a spur gear.



Gear Ratio

Each gear is designed and cut with a specific number of teeth. When two gears are designed to mesh together, although one gear is larger and one smaller, the teeth on both are the same size. The larger gear will have more teeth and the smaller gear will have fewer teeth.

The gear ratio of a pair of meshing gears expresses a relationship between the number of teeth each gear contains. A ratio is a way of comparing two numbers. It is usually written with the two numbers separated by a colon or as a fraction. The ratios are then reduced to lowest terms.

Example: The ratio of two gears, one with 40 teeth and the other with 20 teeth, is written first as 40:20 or 40/20. In both cases, the ratio should now be reduced to lowest terms. The ratio is reduced to 2:1 or 2/1 .

Reducing a ratio to lowest terms does not change the value of the ratio. Since $\frac{3}{4}$, $\frac{6}{8}$, $\frac{12}{16}$ and $\frac{18}{24}$ are equivalent fractions (they have the same value), they are also equivalent ratios.

Example: You are given the number of teeth on two gears and asked to find the gear ratio.

1. Write a fraction with the larger number of teeth as the numerator (the top number in the fraction) and the smaller number of teeth as the denominator (the bottom number in the fraction).
2. Then reduce the fraction to lowest terms.
3. If the denominator is reduced to 1, it is still shown.
4. The final answer can be expressed as a fraction or a ratio written with a colon.

To reduce a number to lowest terms:

1. See if there is any number that will divide evenly into the numerator and denominator.
2. Divide by that number and write down your answer.
3. Examine the resulting numbers that now make up the fraction.
4. If any further numbers will divide evenly into both repeat Steps 2 and 3.
5. Continue until there are no more numbers that will divide evenly into the numerator and the denominator.
6. The fraction is now reduced to lowest terms.

Example: If the gear and pinion in a spur gear have 48 teeth and 36 teeth respectively, what is the gear ratio?

Write a fraction: $\frac{48}{36}$

Reduce the fraction to lowest terms by dividing the numerator and denominator by 12. This will result in the fraction: $\frac{4}{3}$

The answer can be written as $\frac{4}{3}$ OR 4:3. Note that the smaller number is usually written as the denominator.

The gear ratio is $\frac{4}{3}$ or 4:3.

Finding the number of teeth in the second gear when the gear ratio and the number of teeth in one gear are known:

If you are given the gear ratio of a spur gear and the number of teeth of either the gear or the pinion, you can calculate the number of teeth in the second gear. The gear ratio is an equivalent ratio to that of the ratio of gear teeth to pinion teeth.

1. To calculate the number of teeth, you need to make a proportion that compares the two equivalent ratios.
2. Write the two equivalent ratios separated by an equal sign. One of the terms in the teeth ratio is unknown and can be represented by a letter such as n .
3. You then solve the proportion to find the unknown number of teeth.

Example: If a spur gear has a gear ratio of 3:2 and the gear has 33 teeth, how many teeth does the pinion have?

Set up the proportion: $\frac{3}{2} = \frac{33}{n}$

Solve for n by first isolating it on the left side:

$$n = \frac{33 \times 2}{3}$$

Finish by carrying out whatever operations are necessary to find the value of n .

$$n = 22$$

The number of teeth on the pinion is 22.

Speed Ratio

The speed ratio of a pair of meshing gears expresses the relationship between the rotations per minute (rpm) of each gear. It is also usually expressed as a fraction or ratio reduced to lowest terms. The speed ratio is the *inverse* of the gear ratio. Just as the larger gear always has more teeth, the smaller gear or pinion will always rotate at a higher rpm.

- ◆ If you know the gear ratio, you can find the speed ratio by reversing the fraction.
- ◆ For example, if the gear ratio is 5:1 or 5/1, the speed ratio will be 1:5 or 1/5.

Example: What is the speed ratio on a spur gear with 45 teeth on the gear and 15 teeth on the pinion?

First find the gear ratio: $45/15 = 3/1$

Reverse the gear ratio to get the speed ratio.

The speed ratio is 1/3.

In the same way that you found the unknown number of teeth in a gear, if you know the speed ratio and the rpm of one gear, you can find the rpm of the second.

1. The speed ratio and the ratio of the rpm of one gear to the rpm of the second are equivalent ratios.
2. Set up a proportion using the equivalent ratios, using a letter such as r to represent the unknown rpm.
3. Solve the proportion to find the value of r .

Example: If the speed ratio is 4:1 and the rpm of the pinion is 240, what is the rpm of the gear?

Set up the proportion: $\frac{4}{1} = \frac{240}{r}$

Solve for r by first isolating it on the left side:

$$r = \frac{240 \times 1}{4}$$

Finish by carrying out whatever operations are necessary to find the value of r .

$$r = 60$$

The rpm of the gear is 60.

If you know the gear ratio and the rpm of one of the gears, you can find the rpm of the second gear. Reverse the gear ratio to get the speed ratio and then proceed as in the last example.

Example: If there are 36 teeth on the gear and 24 teeth on the pinion in a spur gear and the speed of the gear is 40 rpm, what is the speed of the pinion?

First find the gear ratio: $36/24 = 3/2$

Reverse the gear ratio to get the speed ratio. The speed ratio is $2/3$.

Now solve the proportion using the speed ratio.

First set up the proportion: $\frac{2}{3} = \frac{40}{r}$

Solve for r by first isolating it on the left side:

$$r = 40 \times 3 \left(\frac{40 \times 3}{2} \right)$$

Finish by carrying out whatever operations are necessary to find the value of r .

$$r = 60 \text{ rpm}$$

Torque Produced by a Gear

The torque produced by a gear is equal to the force multiplied by the radius of the gear. (Note that the units of torque are the meter newton in the metric system and the pound foot in the imperial system.)

Example: How much torque is produced by a gear with a radius of .1 meter if a force of 25 newtons is applied to the gear?

$$\begin{aligned}\text{torque} &= \text{force} \times \text{radius} \\ &= 25 \text{ n} \times .1 \text{ m} \\ &= 2.5 \text{ meter newtons}\end{aligned}$$

THE PULLEY

A pulley changes the direction of movement. Pulling down to move something is easier for us than lifting up. A pulley is made by running a rope over a supported wheel. If a load is attached to the rope, it can be lifted up by pulling down on the other end of the rope.

Several pulleys can be connected to form lifting systems that not only change the direction of the force but also amplify the force. An example is a block and tackle.

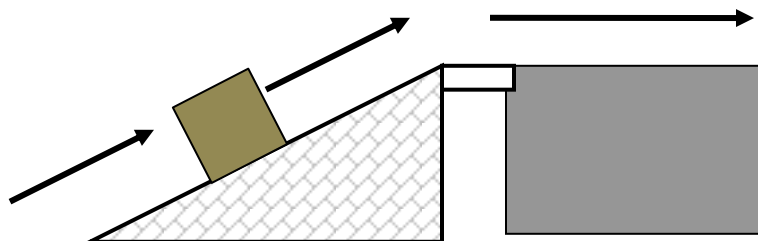
THE INCLINED PLANE

If you want to raise an object to a certain height, you must do a certain amount of work. You cannot reduce the amount of work, but you can change the way the work is done.

If you want to raise an object to a certain height, you must do a certain amount of work. You cannot reduce the amount of work, but you can change the way the work is done.

Work has two aspects: the effort put into it and the distance the effort is maintained.

- When raising an object, you can move it up on a slant rather than lifting it directly up.
- This increases the distance you need to apply your force over while reducing the amount of force needed.
- When you raise an object by pushing or pulling it up an inclined plane or a ramp, less force is needed than if you were lifting straight up, because the force is applied over a longer distance. See Figure 4.



Using an inclined plane to raise a load requires less force but the load must be moved a longer distance

FIGURE 4: The Inclined Plane

THE SCREW

A screw is an inclined plane rolled into a cone. If you take a piece of paper cut into a right triangle (an inclined plane) and roll it up, it looks like a screw. The distance between two adjacent edges of the rolled up paper or between the threads of a screw is called the pitch. See Figure 5.

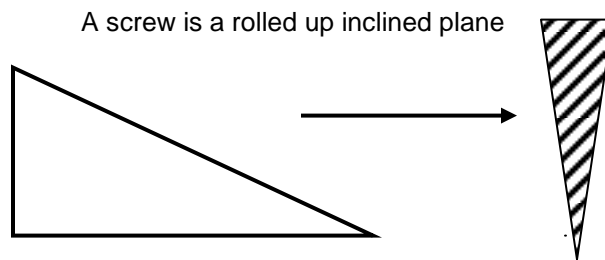


FIGURE 5: The Screw

A screw can have a very large mechanical advantage, but it is an inefficient machine because of the large amount of friction that occurs between the wood or metal and the turning screw. However, this friction helps hold the screw tightly.

The screwdriver used to turn the screw is a third class lever where your wrist is the fulcrum, your hand supplies the effort force and the head of the screw is the resistance. Some of the effort force applied to the screw by the screwdriver parts the wood as the screw turns.

THE WEDGE

The wedge is a double-sided inclined plane. A wedge acts as a moving inclined plane. Most cutting machines like axes and saws make use of a wedge. When a saw cuts a board, some of the forward movement of the saw is converted into sideways movement in the wood. The sideways movement splits open the board. A shovel acts as a wedge when it cuts through soil. It then acts as a lever when you lift and move the dirt.

ACTUAL AND IDEAL MECHANICAL ADVANTAGE

Machines give us a **mechanical advantage (MA)**: *an advantage gained in the amount of work done by the use of a mechanism in transmitting force.*

Work is a force applied over a certain distance. It is the combination of both force and distance that determines the work done when moving an object. A machine can increase the amount of force applied or it can increase the distance over which the force is applied.

When we try to move an object, our applied force must overcome the resistance forces that act to hold the object in place.

- ◆ The force we use to move an object is called *the applied force or the effort force*.
- ◆ The object's opposition to being moved is called the *resistance force or the load*.
 - Resistance forces include the force of gravity and the force of friction that act on the mass of the object.
 - In simple situations, the load or resistance force is considered to be the same as the force of gravity, which is calculated as the weight of the object.

Most simple machines increase the distance over which the force is transmitted.

- When you use a crowbar to pry a large unit into its exact position, the crowbar provides a longer distance over which to apply the force of your muscles.
- You move a heavy object more easily and more accurately using a lever. The lever gives you the advantage of greater distance from the object to be moved.

Mechanical advantage is expressed as a ratio which indicates how much help the machine provides.

Actual Mechanical Advantage

The *actual mechanical advantage* of a simple machine (MA) is found by using *the ratio of the resistance force (F_L) or the weight of the object being moved, to the effort force (F_E)*.

$$MA = \frac{F_L}{F_E}$$

The resistance or load force is the force that results from the weight of the object to be moved. The effort force (F_E) is the force applied by the person using a machine to move the object.

The smaller our effort in relation to the weight moved, the greater the actual mechanical advantage. If a machine such as a wheeled cart allows you to move a 200 lb load using 40 lb of applied force from our muscles, the wheels have given you a mechanical advantage.

Note: When you divide to find the actual mechanical advantage of a machine both the load and the effort force have the same units, they cancel out.

Example: If you move an object with a weight of 200 lb using a machine and the force you apply is 40 lb, what is the mechanical advantage of the machine?

$$\text{mechanical advantage} = \frac{\text{load weight}}{\text{effort force}}$$

$$MA = \frac{F_L}{F_E}$$

$$MA = \frac{200 \text{ lb}}{40 \text{ lb}}$$

$$MA = 5$$

The actual mechanical advantage is 5.

The actual mechanical advantage ratio compares two forces, the force of the load and the force of the effort. There is a second ratio called ideal mechanical advantage that compares the distances over which the two forces are applied.

Ideal Mechanical Advantage

The *ideal mechanical advantage* is the ratio of the distance the effort force moves (s_E) to the distance the load moves (s_L).

$$\text{Ideal MA} = \frac{S_F}{S_I}$$

Imagine you need to raise a heavy crate, one you cannot lift, 4 feet from the floor to the bench. Four feet is the distance the resistance force moves. You push it up a 10 foot long ramp. Ten feet is the distance the effort force moves. By using the ramp to move the crate which is too heavy to lift, you have gained a mechanical advantage.

A ramp is an example of an inclined plane. It gives us a mechanical advantage because it allows us to carry or push something up a slope using less force than lifting it straight up.

When we use an inclined plane, we use less force to lift an object, but we have to apply the force over a longer distance. We use loading ramps to load trucks so we can prevent injury to workers and equipment.

Example: What is the ideal mechanical advantage of a lever if the effort force is applied at a distance of 8 meters from the fulcrum to move a load that is 2 meters from the fulcrum?

$$\begin{aligned}\text{Ideal MA} &= \frac{S_F}{S_I} \\ &= \frac{8m}{2m} \\ &= 4\end{aligned}$$

Efficiency of a Machine

The efficiency of a machine is the ratio of work output over work input. It is usually expressed as a percentage. An ideal machine would be 100% efficient. In reality, machines lose energy as heat from friction. In our examples, we have been ignoring the effects of friction.

The efficiency of a machine such as a lever or an inclined plane depends on four different factors:

- ◆ the resistance force or load
- ◆ the applied force or effort
- ◆ the distance the load moves through
- ◆ the distance the applied force moves through

$$\text{efficiency} = \frac{\text{force} \times \text{distance of the load}}{\text{force} \times \text{distance of the effort}}$$

CONCLUSION

In the machining and tooling trades, you use both simple and complex machines. Understanding how simple machines work can help you use tools and machinery efficiently and safely in the various aspects of your job.

Simple machines such as levers, gears, wrenches and hammers illustrate the principles of mechanical advantage. Complex machines such as motors, drill presses, hoists and conveyor belts operate on the basic principles of simple machines. Knowing about simple machines can help you interpret how more complex machines are constructed and how they run.

Both simple and complex machines work to ensure that you have the correct amount of force to produce the necessary movement in the right place. With the mechanical advantage provided by a machine such as a hoist, you can lift a heavy load that requires more force than your muscles can supply. Other machines such as power tools enable you to do some jobs much faster.

**Answer the following questions by filling in the blank spaces with one of these words.
The answers are at the end of this skills manual.**

lever force longer less hammer second class fulcrum
shovel

1. Mechanical advantage is an advantage gained by the use of a mechanism in transmitting _____ .
2. A _____ is a rigid bar that is free to turn about a pivot point called a fulcrum.
3. A wheel barrow is a _____ lever.
4. When a lever is balanced, the resistance force multiplied by its distance to the _____ is equal to the effort force multiplied by its distance to the fulcrum.
5. When we need to move a heavy object using a lever, we can increase the effectiveness of our applied force by making the length of the lever on the effort side of the fulcrum _____ .
6. When we use an inclined plane to raise an object, the force we need to apply is _____ than when we lift it straight up, but the distance we apply it over is longer.
7. A _____ is a third class lever.
8. Some tools are used to gain mechanical advantage in more than one way. A _____ is an example of both a wedge and a lever.

Answer the following questions by writing true or false in the blanks.

9. Torque refers to a force that produces a turning motion. _____
10. The torque on a bolt depends only on the force applied, not the length of the wrench.

11. A wedge acts like a double sided inclined plane. _____
12. A screw is a rolled up lever. _____

The following questions deal with the relationships between the number of teeth and the rpm of the gear and pinion in spur gears.

13. If a spur gear has a gear with 50 teeth and a pinion with 30 teeth, what is the gear ratio?
14. If the pinion in question 1 was replaced by another with 40 teeth, what would the gear ratio be now?
15. A spur gear with a gear ratio of 3:2 has a pinion with 32 teeth. How many teeth does the gear contain?
16. If a spur gear has a gear with 80 teeth and a gear ratio of 8:3, how many teeth does the pinion have?
17. If the gear ratio of a spur gear is 7:3, what is the speed ratio?
18. If the speed ratio is 4:9, what is the gear ratio?
19. What is the speed ratio on a spur gear with 25 teeth on the pinion and 75 teeth on the gear?
20. If the speed ratio is 1:4 and the speed of the gear is 480 rpm, what is the speed of the pinion?
21. What is the speed of the gear if it has 66 teeth and the pinion has 44 teeth, and the speed of the pinion is 60 rpm?

ANSWER PAGE

1. force
2. lever
3. second class
4. fulcrum
5. longer
6. less
7. hammer (fishing rod, tweezers)
8. shovel
9. true
10. false
11. true
12. false (it is a rolled up inclined plane)
13. $5/3$ or 5:3
14. $5/4$ or 5:4
15. 48 teeth
16. 30 teeth
17. $3/7$ or 3/7
18. $9/4$ or 9/4
19. $1/3$ or 1/3
20. 1920 rpm
21. 40 rpm