EVALUATING
ACADEMIC READINESS
FOR APPRENTICESHIP TRAINING
Revised for
ACCESS TO APPRENTICESHIP

SCIENCE SKILLS
SIMPLE MACHINES & MECHANICAL ADVANTAGE

AN ACADEMIC SKILLS MANUAL
for
The Small Motors Service Trades

This trade group includes the following trades:
Marine & Small Powered Equipment Mechanics,
Motorcycle Mechanics, and
Small Engine Mechanics

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 & MECHANICAL ADVANTAGE

An academic skill required for the study of the Small Motors Service Trades

INTRODUCTION

Humans have always used whatever tools they could find or invent to help make life easier. Tools such as levers, hoists and screw drivers are simple machines that are used to help you complete a job more efficiently. When you lever a heavy unit into place, hoist an engine block or screw something together, you take advantage of the mechanical advantage these simple machines provide. Hammers, carts, levers, screwdrivers and pulleys are examples of simple machines that have long been used to make work easier.

Although the design of each of these machines is simple, the help they provide is significant. Simple machines make work easier by increasing the force you have available. The increase in force provided by a machine gives a mechanical advantage compared to using only your muscles. In the motive power trades, you will lift, carry, balance and hold heavy or unwieldy objects. Understanding how to use simple machines can help you do these tasks more easily.

The main types of simple machines are:
- the lever, from which the pulley, and the wheel and axle developed;
- the inclined plane, from which the screw and the wedge developed.

Simple machines are put together in various ways to create more complex machines such as engines or power tools. These machines require an outside source of energy such as gasoline or electricity.

In this skill manual, we will look at simple machines and the mechanical advantage gained by using a machine, including:

- Definitions of work and power
- Different ways machines increase force
- The lever
- The wheel and axle
- 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*. To find the work done in moving an object, the force applied is multiplied by the distance the object is moved.

Work = Force x distance

The metric unit of work is the joule. *A **joule** (j) 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.

Power = work / time

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

DIFFERENT WAYS MACHINES INCREASE FORCE

Machines 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.* An electrical generator at a dam can transform the mechanical energy in flowing water to electrical energy. A power mower converts electrical energy into mechanical energy used to cut the grass.
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.*** 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 faster on a bicycle than walking. We can move even faster on a complex machine with an outside source of energy such as a motorcycle.

HOW A SIMPLE MACHINE WORKS

hen 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 move a large block out of the way.
    - Work is done on the long arm of a lever at the point where your muscles apply a force by pushing down. This causes the lever to move.
    - Work is done by the lever where the shorter arm of the lever moves up. As the lever moves up, it causes the load or block to move.
    - This results in the block moving.

- The pry bar, a simple machine, enables you to take a tire off a wheel rim that you couldn't pull off with your fingers.
    - The applied force occurs in your arm and the shaft of the bar, up to where it bends.
    - The resistance force or the load occurs in the bar, after the bend, at the tire edge.
    - When you pry the tire out, you move the applied force (your arm and crowbar shaft) a certain distance.
    - The load, (the crowbar end and the tire edge), also moves when you press on the crowbar, although they move a shorter distance.
    - The short amount the tire edge moves is enough to pull it off the rim of the wheel

The work done to move the load - the block or the tire rim - is the same as the work supplied by the effort force - your arm acting on the lever or the crowbar. 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.

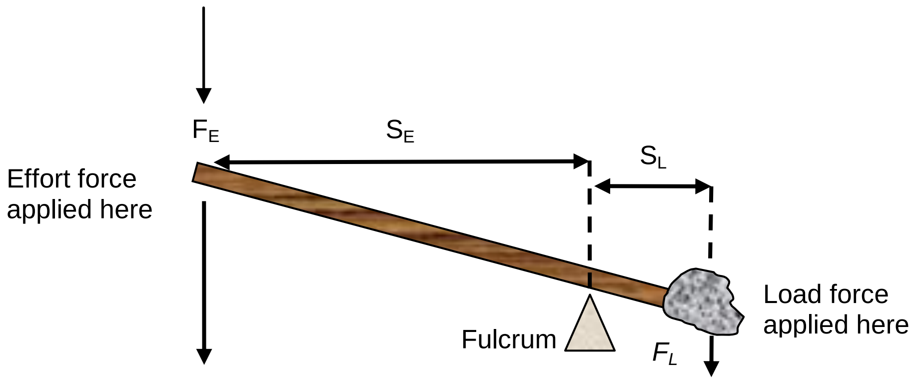


FIGURE 1: Work Done By a Lever

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*.

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

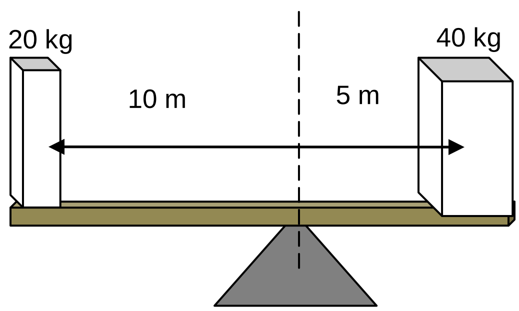
$$D = \frac{20 \text{ x } 12}{60}$$

$$= 4$$

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 n x 10 m = 40 n x 5 m
200 n m = 200 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?

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

F_E = effort force
S_E = 5 ft
F_L = 400 lb
S_L = 1 ft

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

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

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:

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

F_E = effort force
S_E = 10 ft
F_L = 400 lb
S_L = 1 ft

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

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

F_E = 40

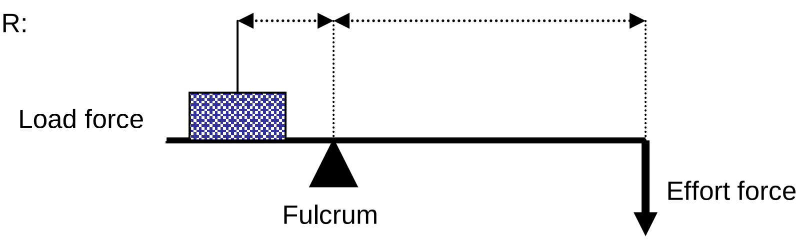
F_E is now only 40 lb. A push of just 40 lbs on your side of the lever at 10 ft from the fulcrum will move the load.

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

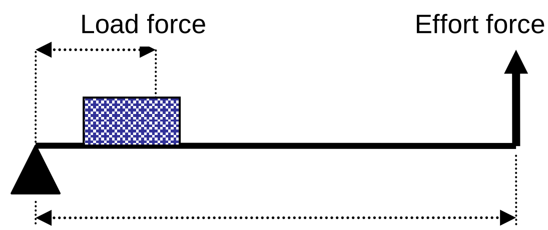
In a lever like the one in Figure 1**,** the fulcrum is placed between the applied force and the load. In other types of levers, the fulcrum can be at one end. The applied force and the load can also be in different positions on the lever. Levers are classified as first, second or third class based on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

FIRST CLASS LEVER:
Example - nail puller



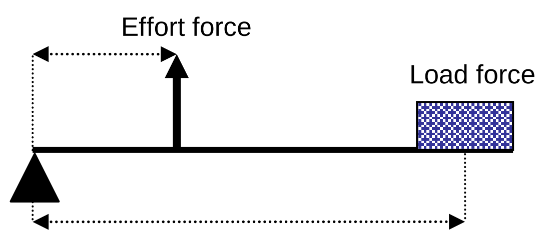
In a first class lever the load force and the effort force are on opposite sides of the fulcrum

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 that results in a turning motion such as the rotation of a wheel is called torque.

TORQUE

Torque *refers to a force that produces a turning motion in an object such as a wheel 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 as it moves up or down.

Torque is measured in the unit *pound foot* in the imperial system and *meter newton* in the metric system.

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.

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.

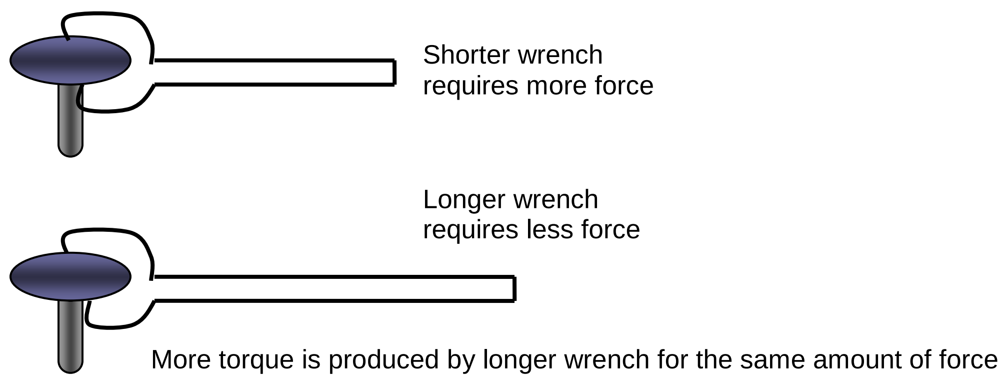


FIGURE 3; Amount of Torque Increases with Size of Wrench

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. Remember that 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.

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.

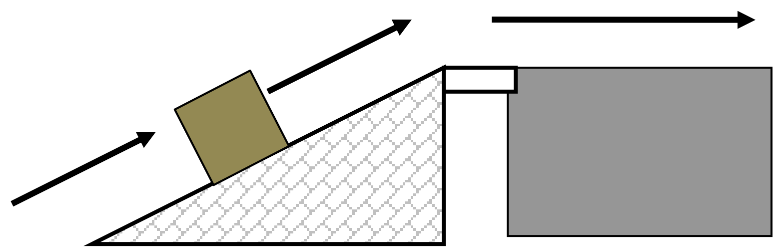
Several pulleys can be connected to form lifting systems that not only change the direction of the force but also amplify the force. An example is a block and tackle.

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.

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.

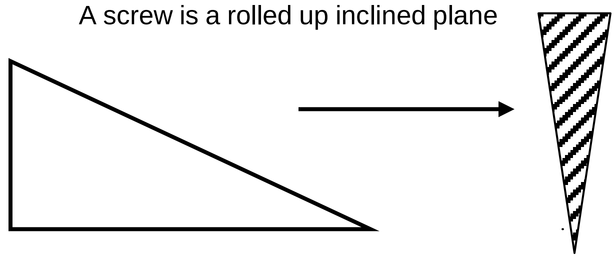


FIGURE 5: The Screw

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 and the turning screw. However, this friction helps hold the screw tightly in the wood.

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.

ACTUAL AND IDEAL MECHANICAL ADVANTAGE

Machines give us a ***mechanical advantage:*** *as 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*.

Examples of resistance force 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 heavy block 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. This ratio indicates how much help the simple 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).*

$$\text{MA} = \frac{\text{F}_\text{L}}{\text{F}_\text{E}}$$

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?

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

$$\text{MA} = \frac{\text{F}_\text{L}}{\text{F}_\text{E}}$$

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

$$\text{MA} = 5$$

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 that two forces are applied over.

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).*

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

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 2 meters?

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

$$= \frac{8m}{2m}$$

$$= 4$$

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.

To find the efficiency of a machine such as a lever or an inclined plan, you have to measure carefully to get accurate quantities for:

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

Then you use your measurements in the following equation to calculate the efficiency of a machine:

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

CONCLUSION

In your work you will move, hold and maneuver heavy objects. You have to drill, hoist, cut and lift. To help you do these tasks efficiently and safely, you use both simple and complex machines.

These 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 the different machines you operate, you can do jobs that require more force than your muscles can supply.

The complex machinery you use is made of simple machines linked together in various ways and driven by an outside source of power. Motors, hoists and lifts all operate on the basic principles of simple machines. Understanding how a simple machine gives a mechanical advantage can help you interpret how a complex machine, such as a garden tractor, works.

Answer the following questions by filling in the blank spaces with one of these words. The answers are on the last page.

lever force longer less hammer mechanical advantage
fulcrum distance

1. Mechanical advantage is an advantage gained by the use of a mechanism in transmitting _______________ .

2. To find the actual _________________ _________________ of a lever, the resistance force (the weight of the object to be moved) is divided by the effort force applied.

3. The ideal mechanical advantage is the ratio of the ______________ the effort force moves compared to the distance the resistance force moves.

4. A _________________ is a rigid bar that is free to turn about a pivot point called a fulcrum.

5. 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.

6. 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 __________ .

7. 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.

8. A ______________ is an example of a third class 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 on the applied force and the length of the wrench.___________

11. If the resistance force is 48 newtons and the effort force is 12 newtons, the mechanical advantage of the lever is 3. _______________

12. A screw is a rolled up lever. _________________

ANSWER PAGE

1. force
2. mechanical advantage
3. distance
4. lever
5. fulcrum
6. longer
7. less
8. hammer (fishing rod, tweezers)
9. true
10. true
11. false, (it is 4)
12. false (it is a rolled up inclined plane)