Simple machines

Unit 5

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Machines have made it possible for mankind to accomplish some truly amazing things, from building the ancient pyramids of Egypt to landing on the Moon. But it is not just these awe-inspiring achievements. Simpler machines are used in everything from cutting food and wood, to hanging a picture on the wall. Without machines there is no way our relatively weak bodies could lift blocks weighing thousands of newtons or even travel much faster than 5 m/s for long periods of time.

In this unit you will learn about what a machine is and why they enable us to lift heavy loads or move large distances. We will investigate the six classes of simple machines and learn about how to determine their efficiency and what mechanical advantage they offer us.

5.1 Purposes of machines

By the end of this section you should be able to:

- Explain the purposes of a machine.
- List the types of simple machines.

- Determine whether the machines are force multipliers, speed multipliers or direction changers.
- Define the terms load, effort, work output, work input, mechanical advantage (MA), velocity ratio (VR) and efficiency.
- Derive the expression of η = MA/VR from its definition.

What are simple machines?

You could probably list hundreds of different machines. These might range from the vastly complex space shuttle, down to a simple pair of scissors.

A machine is a device that is specially designed or engineered to help make it easier to do **mechanical work**. Remember, from Unit 4 mechanical work is given by:

- $W = Fs$

W = work done in J.

F = force applied.

s = distance moved in the direction of the force.

A machine makes it easier to do work by performing one (or more) of the following:

- **increasing the magnitude of the applied force**
- **changing the direction of the applied force or transferring an applied force from one place to another**
- **increasing the distance moved against the applied force (or the speed the force moves).**

No machine can create extra energy (that would break the law of conservation of energy). In other words, the work you put in cannot be greater than the work you get out. However, as you can see from the list above it is possible to get more force out than you put in. We need to think about this carefully.

When you apply a force to a machine this is referred to as the **effort**. In order to do mechanical work you need to move this effort through a distance. Looking back at our equation for work we could rewrite this as:

- $W = Fs$
- **Work input = effort × distance moved by effort.**

The machine then provides a work output; this may be used to move a force (referred to as a **load**) through a distance). In equation terms:

$W = Fs$

- **Work output = load × distance moved by load.**

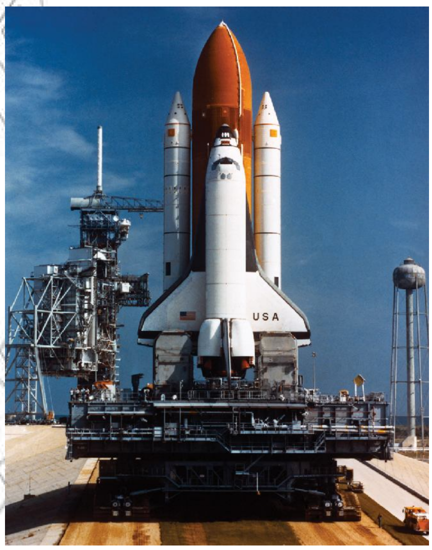


Figure 5.1 Two very different machines!

KEY WORDS

effort *the force applied to a machine*

machines *devices designed to make it easier to do mechanical work*

mechanical work *the amount of energy transferred when an object is moved through a distance by a force*

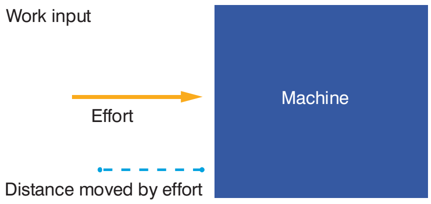


Figure 5.2 Work input to a machine

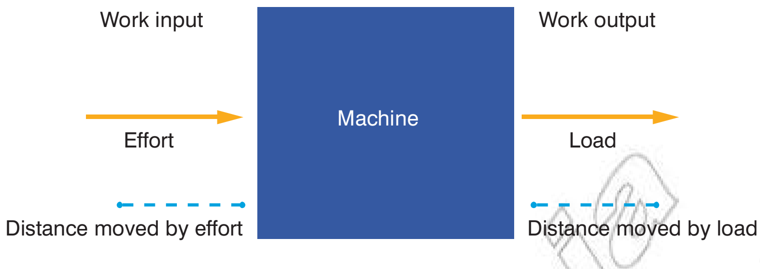


Figure 5.3 A schematic of a machine

If there were no energy losses inside our machine then:

- **Work input = work output**
- **Effort × distance moved by effort = load × distance moved by load**

So, if the machine has been designed so the distance moved by the load is less than distance moved by the effort then the load can be greater than the effort. This means a small effort can be used to move a large load.

For example, imagine a machine that when an effort of 100 N is moved through 2 m it moves a load through a distance of 0.5 m. We can determine the maximum value of the load.

- Effort × distance moved by effort = load × distance moved by load
- 100 N × 2 m = load × 0.5 m
- 200 J / 0.5 m = load
- load = 400 N

The same logic could be used to show it is possible to move a smaller load a bigger distance than the distance moved by the effort.

The term, **simple machine**, refers to a machine that is, well, simple! This has lots of interpretations including:

- **a device that only requires a single force to work**
- **a device for doing work that has only one part**
- **a device that uses a single effort to do work against a single load force.**

Simple machines are often described as the elementary building blocks from which all other machines are made.

Think about this…

There are energy losses in *every* machine. This is usually due to **friction** between the moving parts of the machine. This transforms some of the work input into **heat energy**. As a result, the work input is always greater than the work output (more on this later).

KEY WORDS

simple machine *a device which requires a single effort to do work against a single force*

Different types of simple machine

There are six different types of simple machine; we will look at each of them in turn later.

- **Inclined plane**
- **Wedge**
- **Screw**
- **Lever**
- **Wheel and axle**
- **Pulley**

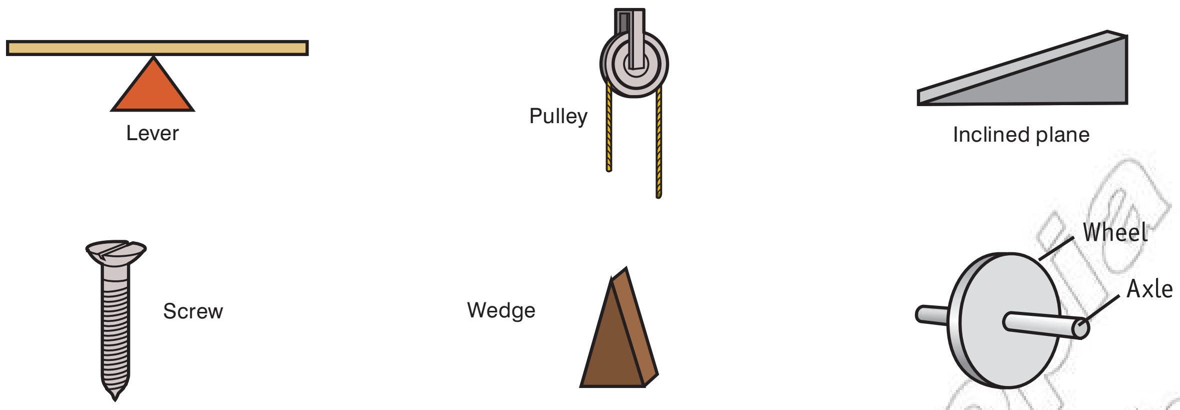


Figure 5.4 *The six different types of simple machines*

Simple machines can be split into two groups. Wedges and screws can be thought of as special kinds of inclined planes. Pulleys and wheels and axles can be considered to be special kinds of levers. We will look at each group in turn in Sections 5.2 and 5.3.

No matter which type of simple machine we deal with they will fit into one or more of the following categories.

Force multipliers

These are machines designed so that the *load is greater than the effort*. This is only possible if the load moves through a smaller distance than the effort.

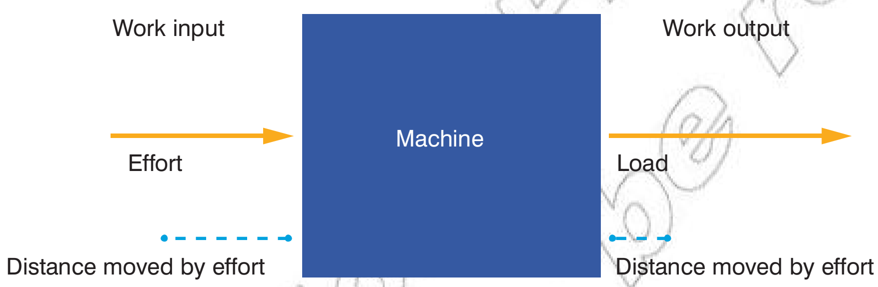


Figure 5.5 *A schematic of a force multiplier. Notice the load is greater than the effort but the distance moved is smaller.*

Speed multipliers

These are machines designed so that the *distance moved by the load is greater than the distance moved by the effort in the same time*. This is only possible if the load is a smaller force than the effort.

DID YOU KNOW?

The famous ancient Greek philosopher Archimedes first came up with the idea of a simple machine around 250 BC. He listed three types of simple machine: lever, pulley and screw. It was not until the Renaissance when Galileo completed the list of all six. He was also the first to realise that simple machines do not create energy.

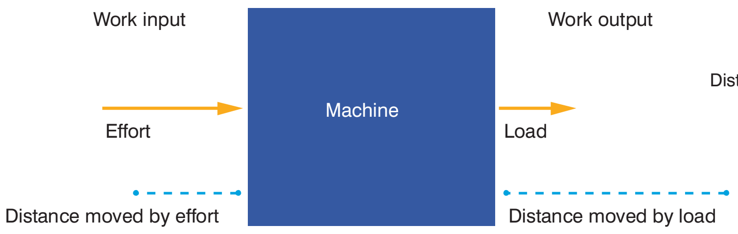


Figure 5.6 *A schematic of a speed multiplier. Notice the load is smaller than the effort but the distance moved is greater.*

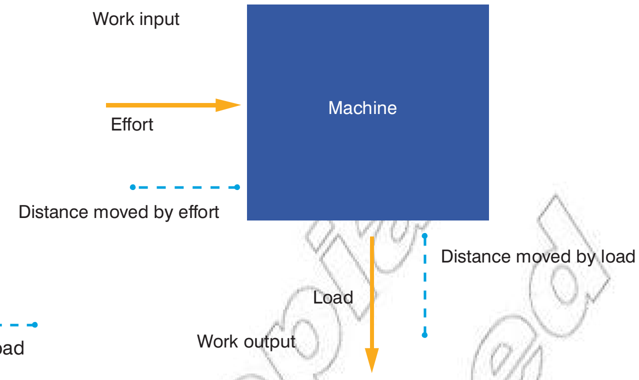


Figure 5.7 *A schematic of a direction changer. Notice the load is moved in a different direction to the effort.*

KEY WORDS

direction changers *machines that move the load in a different direction to the effort*

mechanical advantage *the ratio between the load and the effort*

ratio *the size of quantities relative to each other*

velocity ratio *the ratio between the distance moved by the effort and the distance moved by the load*

Direction changers

These are machines designed so that the *load is moved in a different direction to the effort.*

Depending on how they are designed some machines can act as both force or speed multipliers *and* direction changers. However, a machine cannot multiply both the force and the speed at the same time; this would mean the work output would be greater than the work input.

Mechanical advantage (MA) and velocity ratio (VR)

Some machines are more effective than others. One type of force multiplier might be able to move a 100 N load when 20 N of effort is applied. Another might be able to move a 500 N with the same effort.

It is not just a simple case of the greater the load that can be moved the better the machine, there are a number of other factors. However, there are two terms that are often used to compare different machines. These are **mechanical advantage** (MA) and **velocity ratio** (VR).

Mechanical advantage (AMA and IMA)

The term mechanical advantage refers to the **ratio** between the load and the effort. For example, if a machine moves a 400 N load when an effort of 100 N is applied the mechanical advantage is four. In other words you get 4× the force out of the machine. Mechanical advantage can be calculated using the following equation:

- **Mechanical advantage = load / effort**
- **MA = load / effort**

MA has no units since it is a ratio. If the MA is 1 this means that the effort equals the load. If the MA is two the load is twice the effort and if the MA is 0.5 the load is half the size of the effort.

Mechanical advantage is most frequently used to compare force multipliers. If the MA is *greater* than one the machine can be considered a force multiplier (as the load is greater than the effort).

There are actually two kinds of mechanical advantage; we have really been talking about **actual mechanical advantage** (AMA). This compares the force you get out (load) compared with what you put in (effort).

All machines also have an **ideal mechanical advantage** (IMA). This is the mechanical advantage if there were no other energy losses (e.g. no losses through friction, etc.). For most of our calculations and examples we will assume that there are no energy losses. In this case IMA = AMA and so there is no need to distinguish between the two. However, in the real world IMA is always greater than AMA.

Activity 5.1: Mechanical advantage

Complete the following table:

Effort (N)	MA	Load (N)
500	2	
30		120
360	0.5	
	0.2	1000

KEY WORDS

actual mechanical advantage *the ratio between the load and the effort taking into account energy losses due to friction etc*

ideal mechanical advantage *the ratio between the load and the effort, assuming no other energy losses*

Velocity ratio (VR)

The term velocity ratio refers to the ratio between the distance moved by the effort and the distance moved by the load. For example, if an effort has to move 30 m in order to move a load 3 m then the velocity ratio is 3.

- **Velocity ratio = distance moved by effort / distance moved by load.**
- **VR = distance moved by effort / distance moved by load.**

Just like MA, VR has no units since it is a ratio. If the VR is 1 this means that the effort and the load both move the same distance. If the VR is 2 then the effort has to move twice as far as the load and if the VR is 0.5 then the load ends up moving twice as far as the effort.

Activity 5.2: Velocity ratios

Complete the following table:

Distance moved by effort (m)	VR	Distance moved by load (m)
0.16	4	
0.5		1.5
2	0.5	
	0.1	1

If the VR is *less* than 1 the machine can be considered a speed multiplier (as the distance moved by the load is greater than the distance moved by the effort).

Think about this...

You will need to think carefully about what the VR number represents. You might think a VR of 3 means the load moves 3x further than the effort. This is not true! In fact the load will move a third of the distance (i.e. 1/3).

Efficiency of machines

As discussed earlier, no machine can increase both the magnitude and the distance of a force at the same time. This would break the law of conservation of energy. When a machine provides an

Worked example

A simple machine provides a work output of 120 J for every 480 J of work input. Its efficiency would be given by:

η = work output / work input *State principle or equation to be used (definition of efficiency)*

η = 120 J / 480 J *Substitute in known values and complete calculation*

- η = 0.25 (or 25%) *Clearly state the answer (either as a decimal or as a percentage)*

To find the work output if 2800 J of work goes into the machine we need to rearrange the equation:

η = work output / work input *State principle or equation to be used (definition of efficiency)*

work output = η × work input *Rearrange equation to make work output the subject*

work output = 0.25 × 2800 J *Substitute in known values and complete calculation*

work output = 700 J *Clearly state the answer with unit*

We could then use our equations for work input and output to determine the effort and/or load if the other variables are known.

If the efficiency is one then this means the machine is 100% efficient; there are no energy losses and so the work output equals to the work input. Remember, no machine is ever 100% efficient.

Think about this...

Why can't the efficiency be greater than 1? What would this mean?

increase in force there must always be a decrease in the distance the force is moved. The reverse is also true; if a machine provides an increase in the distance the force moves then there will be a decrease in force (another way to think about this is that no machine can produce more work than the amount of work that is put into the machine).

The term **efficiency** (given the symbol η) is the ratio between the work output and the work input. It is often then multiplied by 100 to give a percentage. The equation is as follows:

- **Efficiency = work output / work input**
- **η = work output / work input**

Just like MA and VR, efficiency has no units since it is a ratio.

If the efficiency of a machine is 0.8 (or 80 %) this means that you would get 80 J of work out for every 100 J you put in. If you put in 500 J you would get 400 J of work out.

We can also express efficiency in terms of MA and VR by expanding our equations for work output and work input:

- **Efficiency = work output / work input**
- **Efficiency = (load × distance moved by load) / (effort × distance moved by effort)**
- **load / effort = AMA**
- **distance moved by load / distance moved by effort = 1 / VR**

So

- **efficiency = AMA / VR**
- **η = AMA/VR**

So a machine with an MA of 6 and a VR of 8 has an efficiency of:

η = AMA/VR = 6 / 8 *Substitute in known values and complete calculation*

η = 0.75 (or 75%) *Clearly state the answer (either as a decimal or as a percentage)*

If AMA = VR then the machine would be 100 % efficient.

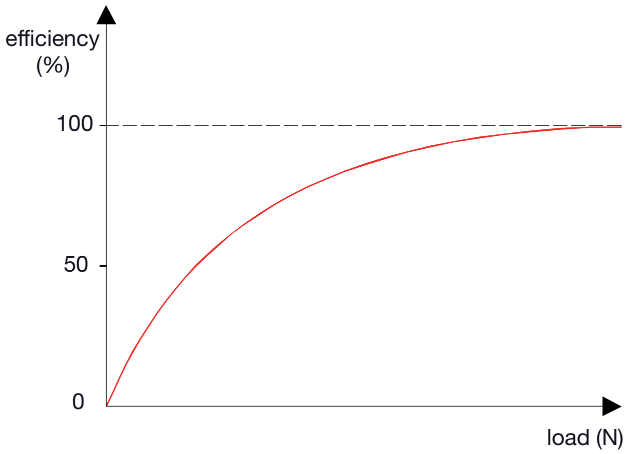


Figure 5.8 *The efficiency of a machine increases as the load increases.*

If the machine was 100% efficient then:

- η = AMA/VR = 1
- AMA = VR

In this case as there are no energy losses then the AMA would be equal to the IMA and so to calculate IMA we could use:

- AMA = IMA = VR
- IMA = distance moved by effort / distance moved by load

The VR is also equal to the maximum theoretical MA (IMA).

Summary

In this section you have learnt that:

- A machine is a device that makes it easier to do mechanical work.
- There are six different types of simple machine: inclined plane, wedge, screw, lever, wheel and axle, and pulley.
- Machines can be classed as force multipliers/speed multipliers and/or direction changers.
- The force put into a machine is called the effort; this may be used to move a load.
- The work output from a machine is equal to the load × the distance moved by the load.
- The work input to a machine is equal to effort × distance moved by the effort.
- AMA = load /effort.
- VR = distance moved by effort / distance moved by load.
- η = MA/VR can be derived from efficiency = work output / work input and the equations for MA and VR above.
- If the machine is 100% efficient then VR = AMA = IMA.

Review questions

1. List the six kinds of simple machine.
2. Define the terms: effort, load, work input, work output, AMA, VR, efficiency and IMA.
3. A simple machine is able to move a 400 N load a distance of 20 cm when a force of 20 N is moved through a distance of 5.0 m. Calculate:
   a) the work input
   b) the work output
   c) the actual mechanical advantage

Worked example

The following information was collected from a simple machine.

Effort = 300 N, load = 1200 N, distance moved by effort = 15 cm, distance moved by load = 3 cm.

η = AMA/VR *State principle or equation to be used (definition of efficiency in terms of AMA and VR)*

AMA = load / effort = 1200 N / 300 N = 4 *Substitute in known values and complete calculation*

AMA = 4 *Clearly state the answer*

VR = distance moved by effort / distance moved by load = 0.15 m / 0.03 m = 5 *Substitute in known values and complete calculation*

VR = 5 *Clearly state the answer*

η = AMA/VR *State principle or equation to be used (definition of efficiency in terms of AMA and VR)*

η = 4 /5 *Substitute in known values and complete calculation*

η = 0.8 (or 80%) *Clearly state the answer (either as a decimal or as a percentage)*

The efficiency of a particular machine depends on a number of different factors. However, it is always true that as the load increases the efficiency of the machine will also increase.

KEY WORDS

efficiency *the ratio between the work output and the work input*

d) the velocity ratio

e) the efficiency of the machine

f) the ideal mechanical advantage.

4. A simple machine has an efficiency of 0.75 and a VR of 12. Determine the MA and the load that can be moved if an effort of 100 N is applied.

5.2 Inclined plane, wedge and screw

By the end of this section you should be able to:

- Derive an expression for MA of an inclined plane with or without friction.
- Calculate MA, VR and efficiency of an inclined plane.
- Calculate MA, VR and efficiency of a wedge.

The inclined plane

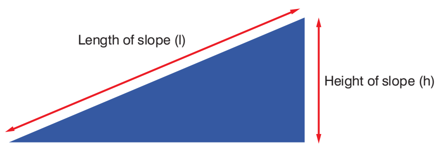


***Figure 5.9** A simple inclined plane*

An inclined plane is just another name for a ramp. The object is lifted to a height (h) by sliding it up the length of the slope (l).

You probably know from experience that it is easier push a heavy object up a ramp than it is to lift it to the same height. This is because inclined planes reduce the force necessary to move a load. In other words, the effort required is less. However, the amount of work done must stay the same so the distance involved increases.

The actual mechanical advantage can be found using the standard equation:

- **AMA = load / effort**

In the case of the inclined plane the load would be the weight of the object and the effort would be to force required to push it up the slope.

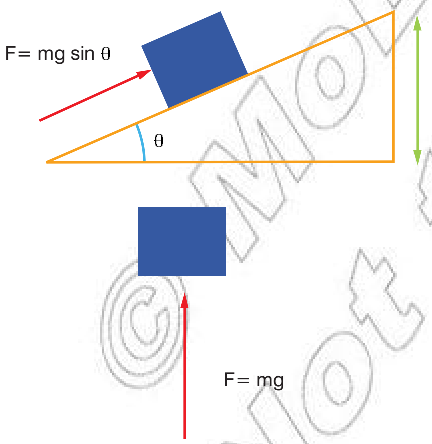


***Figure 5.10** Force required to move an object up a ramp vs. lifting it vertically*

Assuming there is no friction the force required to push the object up the ramp is equal to $mg\sin\theta$. As the angle of the slope increases $\sin\theta$ gets bigger; at 90° it equals one and so then the force required equals mg. In other words, the shallower the slope the lower the force required; however, you would have to push the object a much greater distance to raise it to the same height.

We can derive an expression for mechanical advantage using the dimensions of the inclined plane:

- **Work output = $F s$ = load × h**
- **Work input = $F s$ = effort × l**

If there are no energy losses (i.e. there is no friction), then **work output = work input,** so:

- **load × *h* = effort × *l***
- **load / effort = *l* / *h***
- **load /effort = MA**
- **MA = *l* / *h***

This is really the IMA as we have had to assume that there are no energy losses due to friction. Remember, the IMA is also equal to the VR so the VR for an inclined plane:

- **VR = IMA = *l* / *h***

The gentler the slope, the greater the ratio of the length of its slope to its height. Therefore, the greater the IMA.

The inclined plane can be thought of as a force multiplier and direction changer.

Activity 5.3: Inclined planes

Calculate the VR (and so the IMA) for the following:

1. A slope of length 20 m that rises to a height of 5 m.
2. A slope of length 100 m that rises to the same height.
3. A slope that is at an angle of 30° to the horizontal and rises to a height of 50 m.

In reality, when you push an object up a slope you need to apply an effort greater than $mg\sin\theta$ as you also need to overcome the force due to friction. The force required would equal $mg\sin\theta$ + force due to friction. Therefore the actual mechanical advantage may be found using the following equation:

- AMA = load / effort
- effort = $mg\sin\theta$ + frictional force
- load = mg
- AMA = mg / ($mg\sin\theta$ + frictional force)

The efficiency of an inclined plane can be determined using the standard efficiency equation just applied to inclined planes:

- **η = work output / work input = load × *h* / effort × *l***

Or, in terms of AMA and VR:

- η = AMA/VR
- AMA = mg / ($mg\sin\theta$ + frictional force) and VR = l / h
- η = mgh / ($mg\sin\theta$ + frictional force)l

The wedge

A **wedge** is our second type of simple machine. Wedges are used to separate two objects or split objects apart. Examples of wedges include knives, forks, nails, spears, axes and arrows heads.

Figure 5.11 *The ancient Egyptians used inclines to help in the construction of the great pyramids.*

Think about this…

mgh is the useful work output, whereas ($mg\sin\theta$ + frictional force)l is the work input. Think about this as work done in lifting the object + work done against friction.

Activity 5.4: Including friction

A slope of length 50 m rises to a height of 10 m above the ground. An effort of 100 N is needed to push a 250 N object up the ramp. Calculate:

1. AMA
2. VR
3. efficiency

KEY WORDS

wedge *a piece of material, such as metal or wood, thick at one edge and tapered to a thin edge at the other*

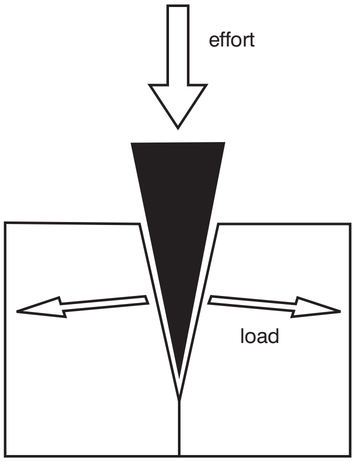


Figure 5.12 *A simple wedge*

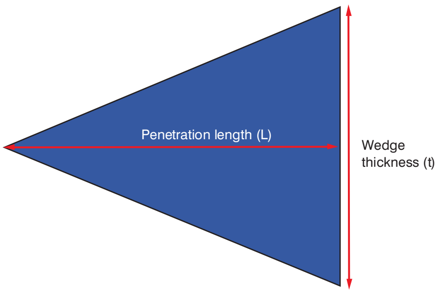


Figure 5.13 *Characteristics of a wedge*

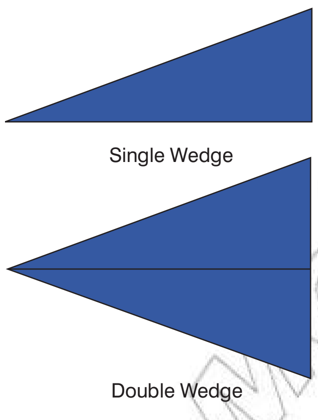


Figure 5.14 *A single or double wedge*

A wedge can either be composed of one or two inclined planes. A double wedge can be thought of as two inclined planes joined together with their sloping surfaces outward.

There are two major differences between inclined planes and wedges. Firstly, when in use an inclined plane remains stationary, whereas the wedge moves. Secondly, the effort is applied parallel to the slope of an inclined plane. When using a wedge the effort is applied to the top of the wedge.

The actual mechanical advantage can be found using the standard equation:

- **AMA = load / effort**

In this case the load would be the force exerted on the object being split and the effort would be the force applied to the top of the wedge.

Just like we did with inclined planes we can derive an expression for mechanical advantage using the dimensions of the wedge:

- **Work output = *F s* = load × *t***
- **Work input = *F s* = effort × *L***

If there are no energy losses (i.e. there is no friction), then **work output = work input,** so:

- **load × *t* = effort × *L***
- **load / effort = *L* /*t***
- **load /effort = MA**
- **MA = *L* / *t***

This is really the IMA as we have had to assume that there are no energy losses due to friction. Remember, the IMA is also equal to the VR so the VR for a wedge = *L* / *t*.

- **VR = IMA = *L* / *t***

The more narrow the wedge, the greater the ratio of the length of its slope to its width. Therefore, the greater the IMA.

Like inclined planes, wedges can be thought of as force multipliers and direction changers.

DID YOU KNOW?

The origin of the wedge is unknown, probably because it has been in use for over 9000 years. In ancient Egyptian quarries, bronze wedges were used to break away blocks of stone used in construction.

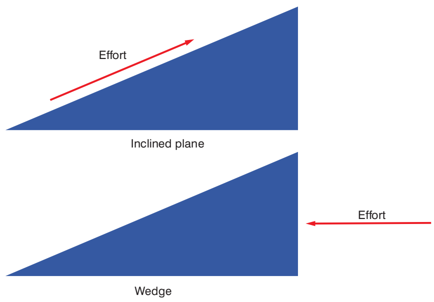


Figure 5.15 *Differences between a wedge and an inclined plane*

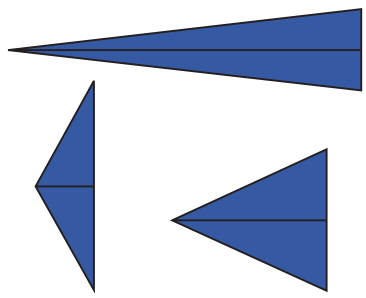


Figure 5.16 *Three different wedges: which offers the greatest IMA?*

The efficiency of a wedge can be determined using the standard efficiency equation just applied to wedges:

- **η = work output / work input = load × t / effort × L**

The screw

The term **screw** really refers to any cylinder with a helical thread around it. This means it includes nuts and bolts as well as more traditional screws. The screw is a very useful machine; it can be used to hold objects together, to dig into the ground and to bore through rocks.

You can think of a screw as like an inclined plane wrapped around a cylinder. In one turn of the screw it digs in and moves into the material a distance equal to the separation between the threads. This is referred to as the pitch (P) of the screw and it is analogous to the height of an inclined plane. If you could unravel a screw thread for each rotation you could see it moves up a distance equal to P. The length of the slope would be the same as the circumference of the screw shaft.

The movement of the screw tip into the material provides the load, whereas the force used to turn the screw is the effort.

The maximum theoretical mechanical advantage (IMA) for a screw can be calculated using the following equation:

- **IMA = πd / P**

d = the mean diameter of the screw shaft in m (πd is the circumference of the screw shaft).

P = the pitch of the screw in m.

There is always a great deal of friction when using screws and the actual mechanical advantage is much less than the value calculated using the equation above. However, it is also worth noting mechanical advantage of a screw system is increased as the screwdriver (or other method for turning the screw) produces its own mechanical advantage.

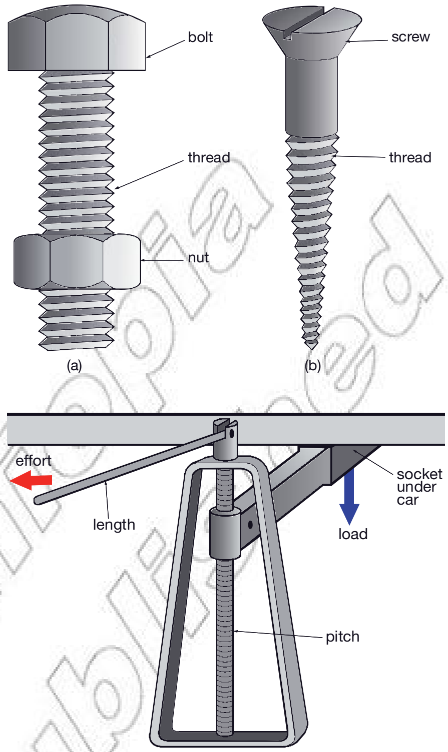


Figure 5.17 Examples of screws

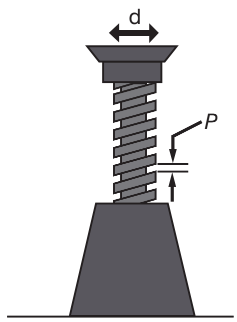


Figure 5.18 Screw characteristics

Figure 5.19 Screw threads

Summary

In this section you have learnt that:

- For an inclined plane the AMA = load /effort, where the load = the weight of the object and the effort = the force required to push the object up the slope ($mg\sin\theta$ + frictional forces).
- If we assume there is no friction on an inclined plane then VR = IMA = length of the slope (l) / height of the slope (h).
- For a wedge the AMA = load /effort, where the load = the force applied to the object being split apart and the effort = the force applied to top surface of the wedge.
- If we assume there is no friction on the wedge then VR = IMA = penetration length (L) / wedge thickness (t).

KEY WORDS

screw *a cylinder of material with a helical thread around it*

Think about this...

The equation for the screw shows how similar a screw and an inclined plane are. πd is equivalent to l and P is equivalent to h. MA for the inclined plane = l / h and for the screw = $\pi d / P$.

DID YOU KNOW?

Some say there are only five different types of simple machine. They argue that the wedge is a just a moving inclined plane. Others say that the screw is just a helical inclined plane; this reduces the list to four!

Review questions

1. For an inclined plane derive $\eta = l / h$.
2. A block of weight 5000 N is pushed up a slope by a force of 250 N. Assume there is no friction. Calculate:
   a) the actual mechanical advantage
   b) the velocity ratio
   c) the length of the slope if the height of the slope is 10 m.
3. An inclined plane is 100 m long and at an angle of 20° to the horizontal. The AMA of the slope is two. Calculate:
   a) the effort required to push a 7200 N block up the slope
   b) the ideal mechanical advantage
   c) the efficiency of the slope.
4. Describe the differences between a wedge and an inclined plane.

5.3 Levers

By the end of this section you should be able to:

- Determine the MA, VR and efficiency of a lever.
- Identify the orders of a lever and give examples.
- Describe the use of a wheel and axle and determine MA, VR and efficiency of a wheel and axle.
- Describe the use of gears.
- Describe different pulley systems and calculate MA, VR and efficiency of a pulley system.
- Describe the use of a jackscrew.

Using levers

A simple **lever** is just a bar that is free to turn around a fixed point. This fixed point is called the **fulcrum** (sometimes the pivot).

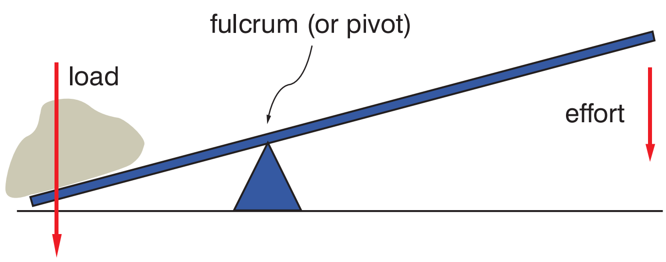


Figure 5.20 *Key features of a simple lever*

Unlike our earlier simple machines levers involve twisting and turning forces.

KEY WORDS

fulcrum *the pivot of a lever*
lever *a bar which is free to turn around a fixed point*

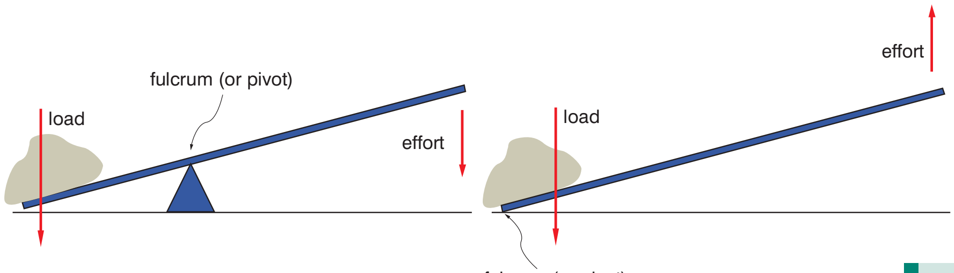


Figure 5.21 *Two different ways to use a lever to lift a load*

MA, VR and efficiency of levers

When dealing with levers the forces are twisting rather than moving in a straight line. As a result we need to think carefully about MA and VR. Let's take a simple example of a balanced see-saw.

In order to balance the turning forces (moments) from both the objects must be equal. The forces might be different but their turning effects must be the same (more on this in Grade 10). In order for an object to balance:

- anticlockwise turning force = clockwise turning force

So in the example below:

- $F_1 \times d_1 = F_2 \times d_2$

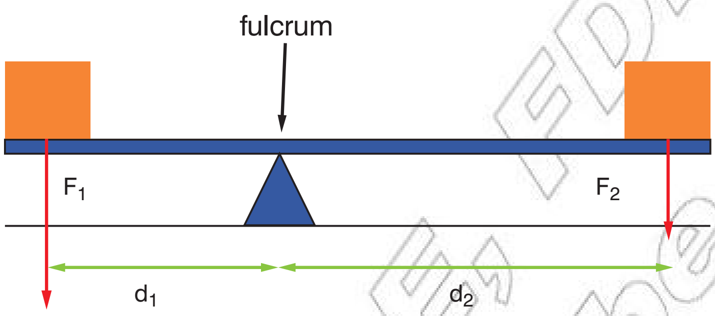


Figure 5.22 *A simple balanced lever*

If F_1 is twice as large as F_2 then F_2 will need to be twice as far away from the fulcrum in order for the see-saw to balance. The **product** of the force and distance for both the left hand side and the right hand side must be equal.

For example, you can balance a 10 N rock with a 0.01 N feather. The feather would need to be 1000 times further from the fulcrum than the rock.

This principle can be applied in terms of load and effort. Imagine the feather was the effort and the rock was the load. The lever has acted like a **force multiplier** with a 0.01 N input force and 10 N output force. Remember, in order for this to be true the effort needs to be applied 1000 times further away from the fulcrum than the load. This leads to the following equation:

- **load** $\times$ d_L = **effort** $\times$ d_E

DID YOU KNOW?

The term lever originates in France; 'levier' means to "to raise".

KEY WORDS

product *the result of multiplying two values*

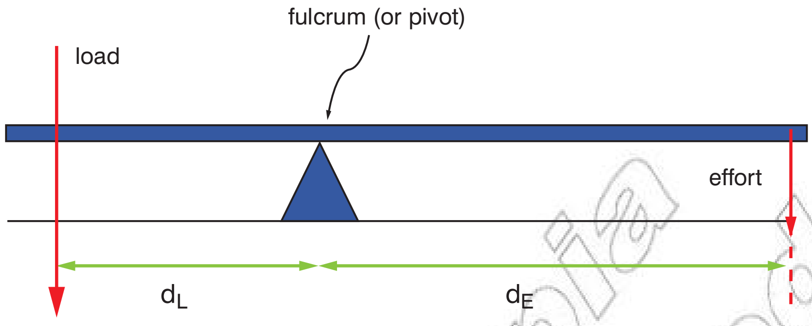


Figure 5.23 The key factors affecting the MA and VR of a lever

Think about this...

The distances to the fulcrum must always be perpendicular to the forces.

It is important to notice that the distances used are always **perpendicular** to the forces. The greater the ratio of d_E to d_L the greater the mechanical advantage (the greater the load you can lift for the same effort). Longer levers make it much easier to lift heavier loads. If you had a really long lever you could lift almost anything (see Did you know?).

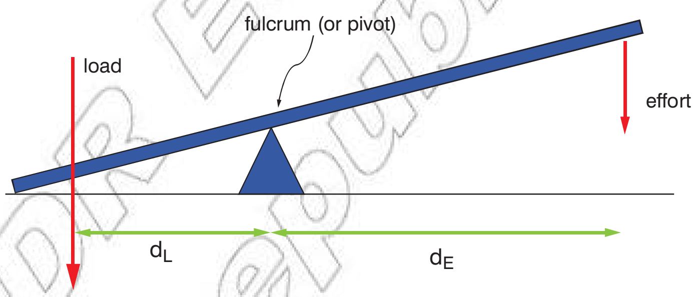


Figure 5.24 Distances perpendicular to forces

DID YOU KNOW?

Archimedes did not invent the lever; instead he wrote the first known explanation of the principles involved. According to Pappus of Alexandria and referring to the MA offered by levers, Archimedes once said: "Give me a place to stand on, and I will move the Earth."

The actual mechanical advantage of the lever is given by the standard equation for MA:

- AMA = load / effort

However, the equation for VR for levers is a little different. As the system is rotating we do not use the distance moved by the force. Instead we use the distances from the fulcrum. The VR can be found as the ratio between the distance from the effort to the fulcrum and the distance from the load from the fulcrum.

- VR = distance from the effort to the fulcrum / distance from the load from the fulcrum.
- VR = d_E / d_L

If there are no energy losses then IMA = VR and so:

- IMA = d_E / d_L

The efficiency of a given lever maybe found via:

- efficiency = η = load × d_L / effort × d_E

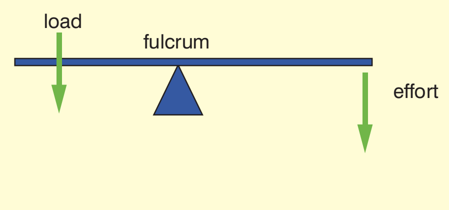
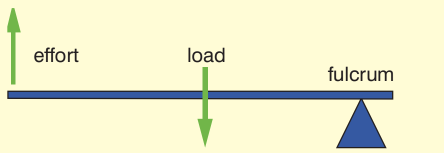
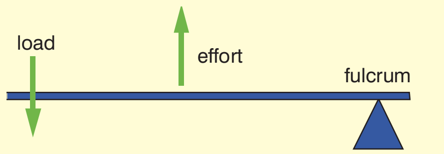
(In terms of MA and VR, η = AMA/VR).

Depending on the relative distances levers can be force multipliers/ speed multipliers and/or direction changers.

Different classes of lever

There are *three* different classes of levers depending on the relative positions of the **load, fulcrum** and **effort**.

Table 5.1 *Different classes of levers*

Class	Diagram	Description	Examples
1st		Fulcrum is between the load and effort	• See-saw • Crowbar • Pliers (double lever) • Scissors (double lever)
2nd		The load is between the effort and the fulcrum	• Wheelbarrow • A rowing oar • Nutcracker (double lever)
3rd		The effort is between the load and fulcrum	• Catapult • Hoe or spade • Tongs (double lever)

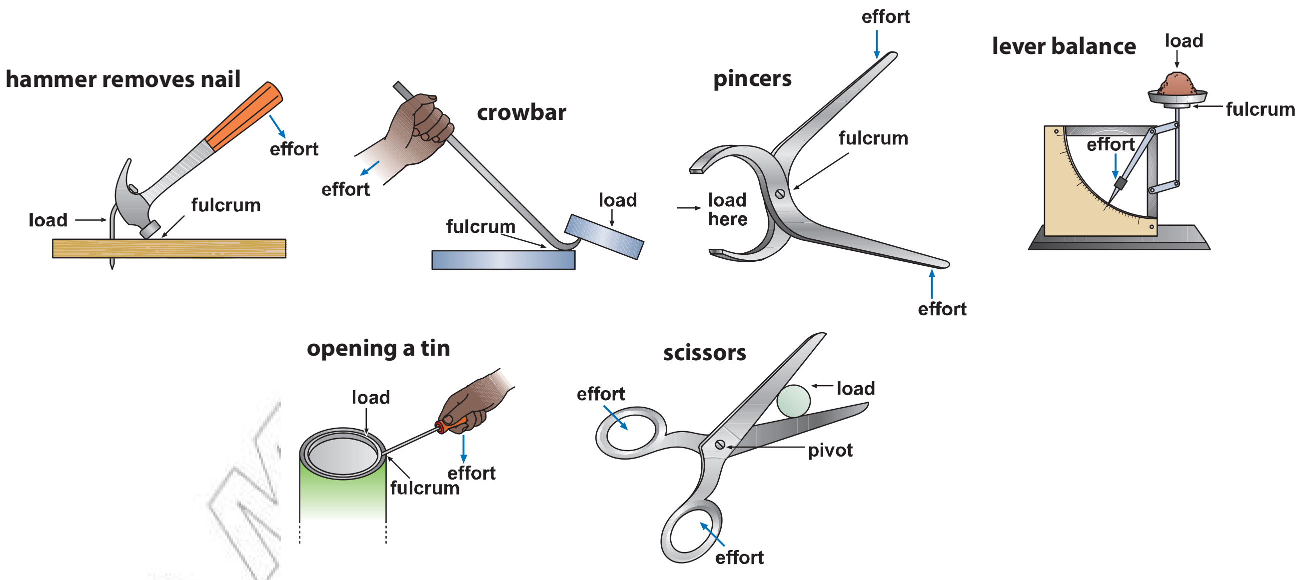


Figure 5.25 *First-class levers have their fulcrum between load and effort. Pincers and scissors are double levers.*

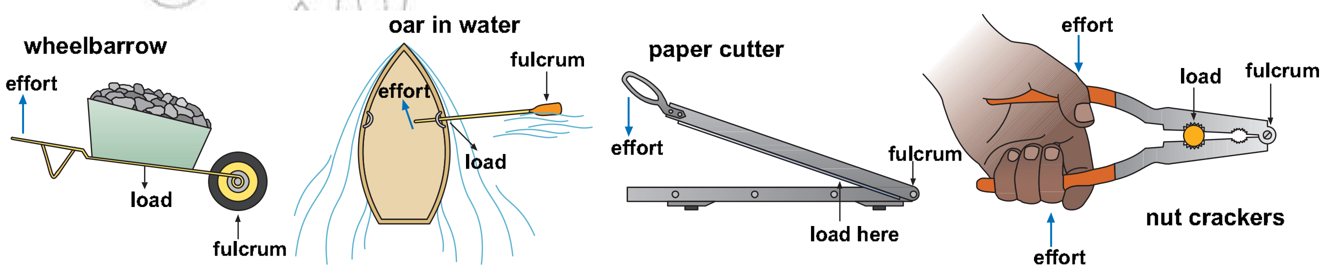


Figure 5.26 *Second-class levers: load between effort and fulcrum*

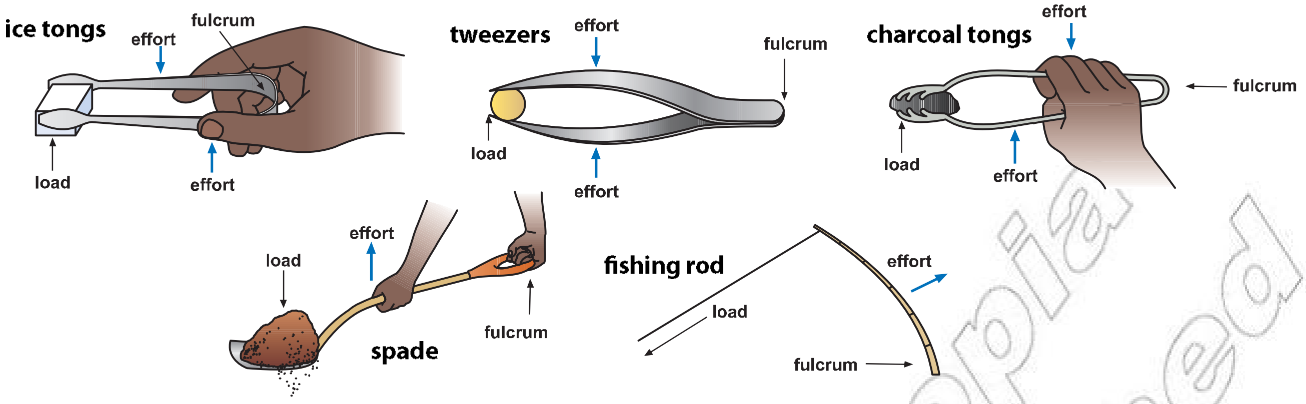


Figure 5.27 *Third-class levers: effort between load and fulcrum*

Activity 5.5: Demonstrating levers

- Use a metre rule, a known weight as the load, and a spring balance as the effort in order to demonstrate the three classes of lever.
- Use cardboard to make a simple label for the fulcrum.
- Make arrows to label the load and effort.

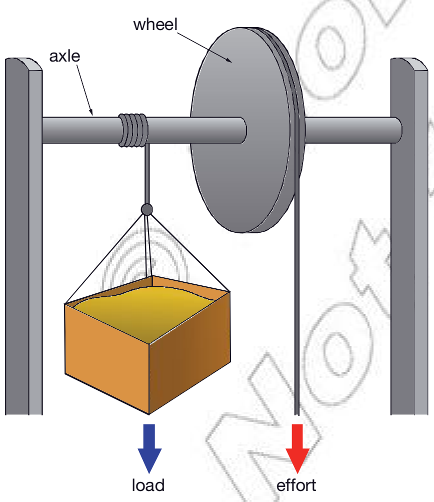


Figure 5.28 *A wheel and axle*

Levers in the body

Examples of the three classes of lever occur in the body:

Table 5.2 *Levers in the body*

	Fulcrum	Load	Muscle providing effort
Head	Joint between head and backbone	Head	Muscle at back of neck
Foot	Toes	Body	Calf muscle (back of leg)
Arm	Elbow	Arm	Biceps muscle (upper arm)

The wheel and axle

The wheel and axle is another type of simple machine; it is comprised of a large wheel secured to a smaller wheel, which is called an axle. Wheels and axles do not just include the obvious; they also include gears, door-knobs, steering wheels and even screwdrivers!

There are two main ways to use a wheel and axle. The first way can be seen in Figure 5.28. You can wrap a rope around a supported wheel and apply an effort to the end of the rope. This causes the wheel and attached axle to rotate. If a load is attached to the axle as it turns it lifts the load. The effort has to move a long way to complete one single revolution (as the diameter of the wheel is large). The load moves a much smaller distance as the axle has a much smaller diameter. This means the load can be much greater than the effort and so there is a mechanical advantage.

The second way to use a wheel and axle is to have two wheels at the end of an axle. The wheel and axle then behaves like a type of rotating lever. In this case the fulcrum would be the centre point of the axle. As the wheels turn they can then be used to provide movement.

The mechanical advantage of a wheel and axle may be calculated using the standard equation for AMA:

- AMA = load /effort

The VR of the wheel and axle is the ratio of the radius of the wheel to the radius of the axle. This is because as the wheel turns once it covers a distance equal to $2\pi R$; in the same time the axle travels $2\pi r$. So the VR is given by:

- **VR = distance moved by effort / distance moved by load**
- **VR = $2\pi R / 2\pi r$**
- **VR = R / r**

If the machine was 100% efficient then VR = MA = IMA so:

- IMA = VR
- IMA = R / r

If the radius of the wheel is ten times greater than the radius of the axle, every time you turn the wheel once, the force will be multiplied by ten but it will also travel ten times the distance.

Depending on the relative radii wheels and axles can be thought of as force multipliers/speed multipliers and/or direction changers.

Figure 5.29 *An example of a wheel and axle*

The effect of gears

Gears are often used in conjunction with a wheel and axle. They can be configured to offer an increase in mechanical advantage or an increase in the distance travelled, depending on the requirements of the system.

As one gear turns its teeth lock into another gear and force it to rotate. The gear made to turn is called the driving gear or occasionally the pinion (the one where the effort is applied). As the driving gear then rotates it turns the driven gear.

The VR of a pair of gears is given by the ratio of the number of their teeth.

- **VR = number of teeth on driven wheel / number of teeth on driving wheel**
- **VR = $N_{driven} / N_{driving}$**

This is also called the **gear ratio**. If the gear ratio was 0.5 then the driven gear would rotate once for every two rotations of the driving gear.

Looking at Figure 5.31, if the left hand wheel was the driving wheel then there would be a VR of less than one. In other words the distance would increase but the effort would have to be greater than the load.

If the driving wheel was the one on the right then the opposite would be true. The load would be greater than the effort but it would not travel as far.

If the machine was 100% efficient then VR = MA = IMA so:

- IMA = VR
- IMA = $N_{driven} / N_{driving}$

Two or more gears together are called a **transmission**. Depending on the gear ratio, transmissions can produce a change the speed, magnitude and direction of a force.

DID YOU KNOW?

It is probably fair to say that the wheel is the most important invention of all time. The oldest wheel was found in Mesopotamia (modern Iraq/Syria). It is believed to be over 5000 years old.

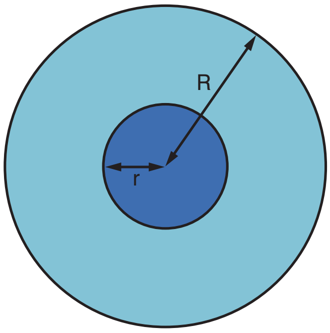


Figure 5.30 *The radii of the wheel and axle are the two factors that determine the VR.*

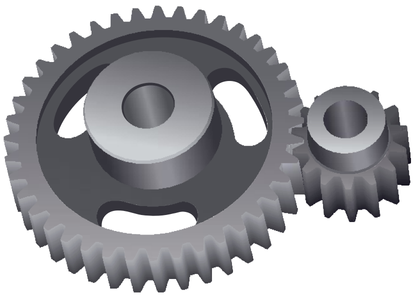


Figure 5.31 *A simple example of a pair of gear wheels*

Figure 5.32 *A rack and pinion*

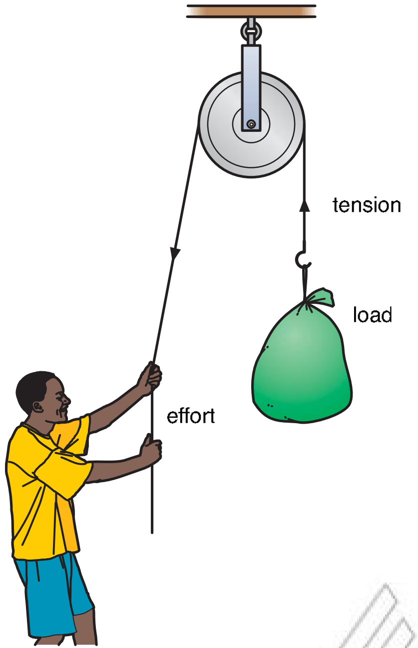


Figure 5.33 *Using a pulley to lift a load*

DID YOU KNOW?

The most common application of gears involves one gear causing another to rotate. However, in a rack and pinion a gear causes a linear toothed track (called a rack) to move. This leads to a movement in a straight line rather than a rotation.

Pulley systems

There are several different kinds of **pulley**. The most simple comprises a fixed axle with a rope looped over the top (called a class 1 or **fixed pulley**). Even if there was no friction, a fixed pulley will not provide more than a mechanical advantage of 1. This means there is no multiplication of force; instead the pulley just changes the direction of the force.

The second type of pulley is often called a **movable pulley**. Here the axle is free to move up and down.

If one end of the rope is fixed then applying an effort to the other end of the rope (after it has been looped around the pulley) will effectively provide about two times the force. However, it is worth noting that you have to provide additional effort to lift the movable pulley as well as the load.

A movable pulley has a VR of 2 as you would have to pull 2 m of rope through the pulley in order for it to lift the load 1 m. If there are no energy losses in the pulley then the VR = MA = IMA. Therefore the IMA for a movable pulley is also 2.

For both a fixed and a movable pulley there will be energy losses due to friction. As a result the MA will always be less than the VR.

A **compound pulley** is a combination of a fixed and a movable pulley. This is sometimes called a block and tackle. The movable pulley provides the MA whereas the fixed pulley changes the direction of the force. This makes it easy to lift the load when standing on the floor!

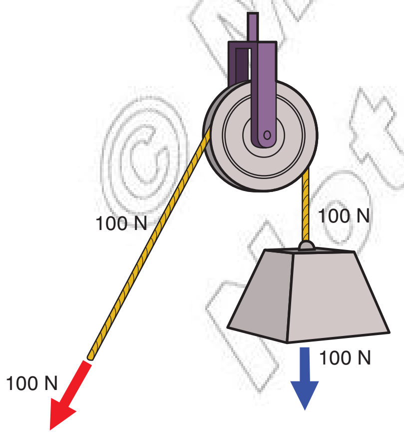


Figure 5.34 *A fixed pulley offers no MA but does change the direction of the force.*

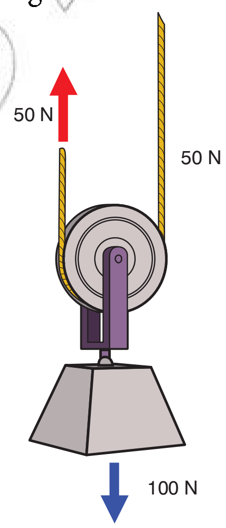


Figure 5.35 *A movable pulley* ***does*** *provide an MA.*

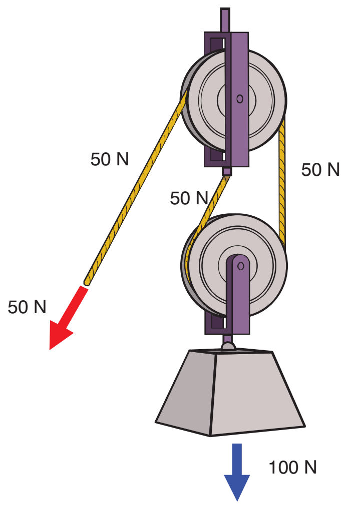


Figure 5.36 *A compound pulley is a combination of a fixed and movable pulley.*

To increase the VR of any block and tackle, a pulley block with more than one pulley in each block can be used. A long length of rope is tied to the top block then passes around each of the pulleys in turn.

The pulleys might be side by side (as in Figure 5.37) or above each other, as shown in the diagram in Figure 5.38.

The VR of these systems is given by the number (*N*) of sections of rope used to lift the load. If there is only one section then VR = 1, if there are two sections then the VR = 2, etc.

- **VR = number of sections of rope that lift the load**
- **VR = *N***

These systems are never 100% efficient since there is friction on the pulley and some of the effort is used to lift the lower block instead of the load. If the machine was 100% efficient then VR = MA = IMA so:

- **IMA = VR**
- **IMA = *N***

***Figure 5.37** A pulley block with three pulleys*

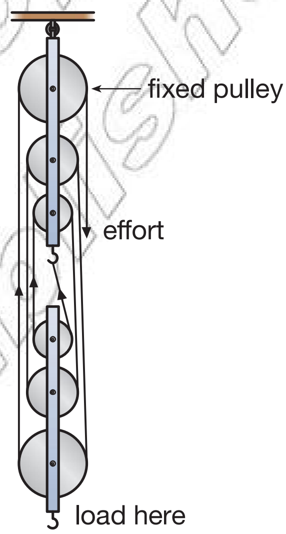


***Figure 5.38** Two pulley blocks with three pulleys in each*

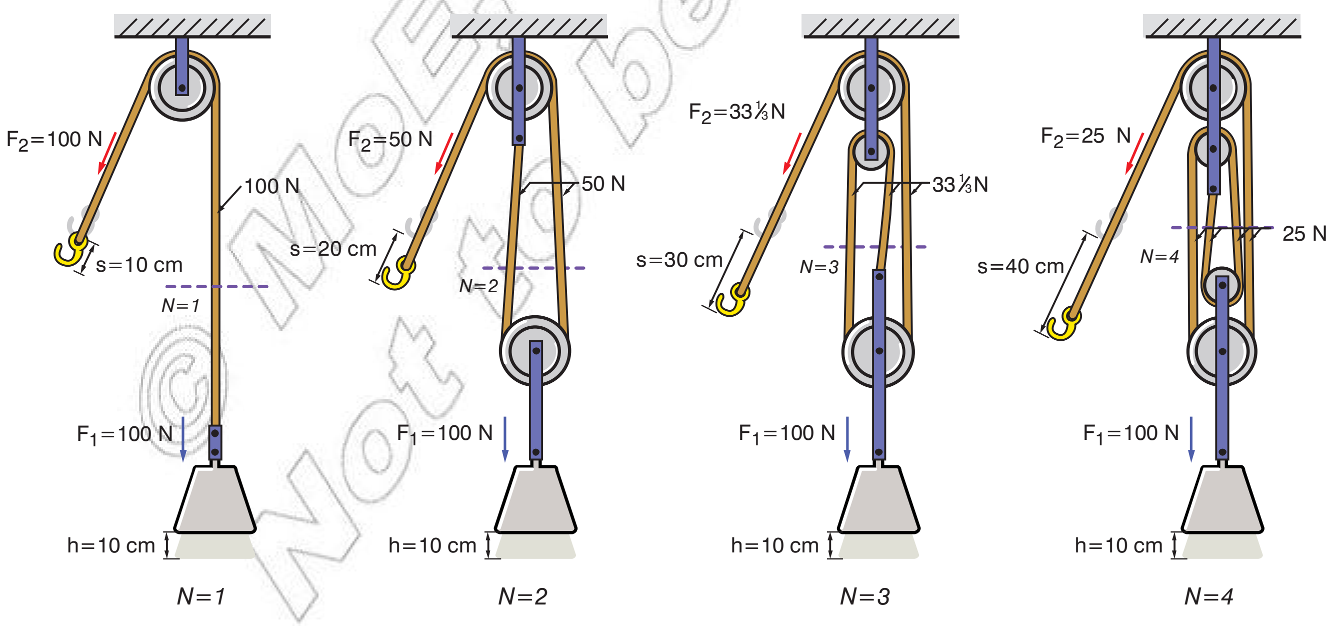


***Figure 5.39** The VR of a pulley system depends on the number of sections of rope that lift the load.*

Think about this...

What advantages and disadvantages are there to changing the diameter of the pulleys wheels, as shown in Figure 5.38? Hint: think about the IMA offered by a wheel and axle.

KEY WORDS

fixed pulley *a grooved wheel on a fixed axle with a rope looped over it*

movable pulley *a grooved wheel on a movable axle with a rope looped round it*

pulley *a simple machine comprising a wheel with a grooved rim over which a rope or chain is passed*

transmission *a set of two or more gears*

complex machine *a device where two or more simple machines are combined to make a single mechanism*

differential pulley *a pulley combined with a wheel and axle*

jackscrew *a screw combined with a lever*

Activity 5.6: Investigating a system of pulleys

- Arrange the pulley blocks as shown in Figure 5.40. Attach a forcemeter to measure the effort. Place a known weight on the lower block. Pull the forcemeter downwards so that the load rises slowly at a uniform speed. Note the steady reading. Repeat and take the average reading. Table 5.3 shows how to record your results.

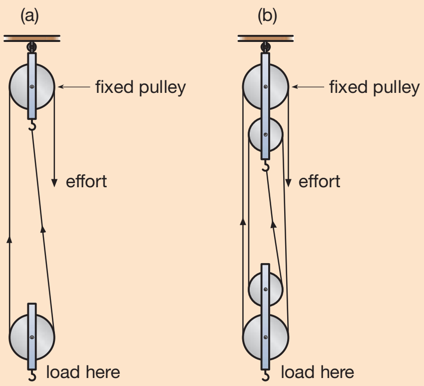


Figure 5.40 *Using (a) two, and (b) four pulleys to raise a load*

- Return the load to its low original position. Note the position on the rule of the load and the hook of the forcemeter (the effort). Raise the load a known distance. Measure how far the effort moves. Repeat and take the average reading.
- Calculate MA, VR and the efficiency.
- Repeat, using different weights as the load.

Table 5.3 *Investigating a system of four pulleys.*

Load	Effort	MA	Distance moved by load	Distance moved by effort	VR	Efficiency
3 N	1.5 N	2.0	10 cm	40 cm	4	50%
5 N	2.0 N	2.5	12 cm	48 cm	4	62.5%
etc.						

The table shows results for a system of four pulleys. The mechanical advantage is less than four and the velocity ratio is exactly four (it is equal to the number of strings holding the load).

More complex machines

A **complex machine** is one where two or more simple machines are combined to function as a single mechanism. Examples include scissors, wheelbarrows, bicycles, the differential pulley and the jackscrew. We will look at two examples in more detail, the differential pulley and the jackscrew.

The differential pulley

A **differential pulley** is a pulley in combination with a wheel and axle. It is sometimes called a "chain hoist" and it can be used to lift extremely large masses over a short distance.

It is composed of two fixed pulleys at the top. These are attached to each other and both rotate together. However, they have different radii (R and r). One long loop of rope (or more commonly a chain) passes around the pulleys. The excess hangs off the pulley in a loop. To lift a load you pull on the loop, causing the pulleys to rotate and slowly lift the load. The mechanical advantage is calculated using the standard equation:

- AMA = load /effort

In this case the load = W and the effort = F so:

- AMA = W / F

The VR (and so the IMA) is given by:

- VR = IMA = $2R / (R - r)$

As $R - r$ approaches zero the IMA increases. If R is about the same as r it almost gets to the stage where the weight looks like it is no longer lifting as you end up pulling long lengths of chain or rope downward for a very small vertical movement. However, you are able to lift very heavy loads.

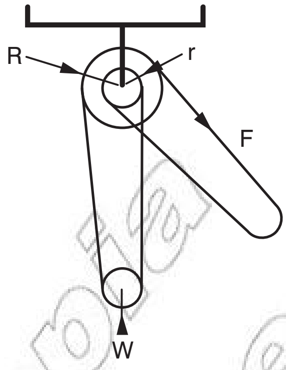


Figure 5.41 *The key features of a differential pulley*

The jackscrew

A **jackscrew** is a screw in combination with a lever. The MA from the lever allows large weights to be lifted by the screw.

The mechanical advantage is calculated using the standard equation:

- AMA = load /effort

In this case the load = W and the effort = F (the force applied at the end of the lever) so:

- AMA = W / F

The VR (and so the IMA) is given by:

- IMA = VR = $2\pi R / P$

The longer the handle (R) and the smaller the pitch (P) the greater the IMA, but it would take even more turns in order to lift the car!

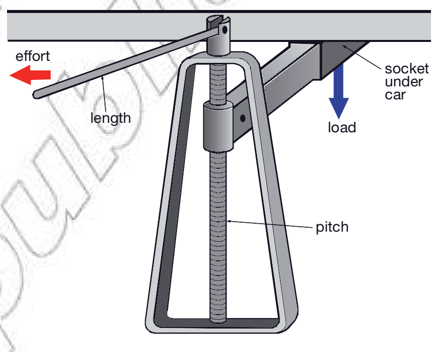


Figure 5.42 *A simple jackscrew used as a car jack*

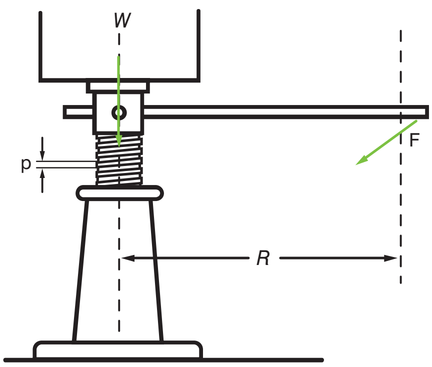


Figure 5.43 *The key features of a jackscrew*

Summary

In this section you have learnt that:

- For a lever the AMA = load / effort and the VR (and so IMA) = distance of the effort to the fulcrum (d_E) / distance of the load from the fulcrum (d_L).
- There are three orders of levers, depending on the relative positions of the load, fulcrum and effort.

- For a wheel and axle the AMA = load / effort and the VR (and so IMA) = radius of wheel (R) / radius of axle (r).
- There are three different types of pulley systems: fixed, movable and compound.
- For a pulley the AMA = load / effort and the VR (and so IMA) = the number (N) of sections of rope used to lift the load.
- A complex machine is a combination of two or more simple machines (for example, a jackscrew is a combination of screw and lever – this can be used to lift very heavy loads).

Review questions

1. Explain how a lever can act as a force multiplier.
2. For the following simple see-saw calculate:
   a) the load that could be lifted
   b) the mechanical advantage (assume the lever is 100% efficient).

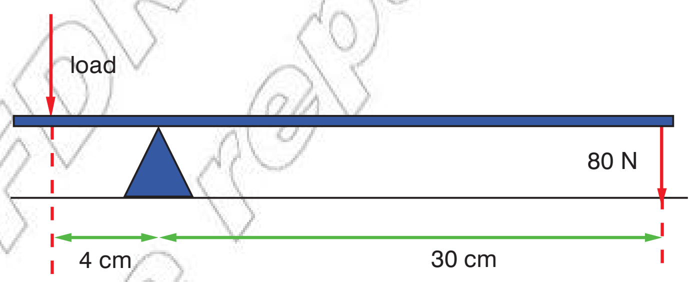


Figure 5.44 *A simple see-saw*

3. A simple wheel and axle is used to lift a bucket of water out of a well. The radii of the wheel and axle are 20 cm and 4 cm, respectively. Determine:
   a) the velocity ratio (and so the IMA)
   b) the theoretical effort required to lift a load of 30 N assuming no energy losses
   c) the efficiency if the actual effort required is 10 N.
4. Describe the three different types of pulley.

End of unit questions

1. Explain why for every simple machine the actual mechanical advantage is less than the ideal mechanical advantage.
2. By giving an example of a simple machine (including its dimensions) explain what is meant by force multiplier, speed multiplier and direction changer.

3. An inclined plane rises to a height of 2 m over a distance of 6 m. Calculate:
   a) the angle of the slope
   b) the VR (and so IMA) of the inclined plane
   c) the theoretical force required to push an object with a mass of 200 kg up the slope.
4. Give three examples of wedges.
5. A 10 cm long, 2 cm wide wooden wedge is pushed into a soft wood block. Calculate:
   a) the velocity ratio of the wedge
   b) the load on the soft wood if the effort applied is 30 N (assuming the wedge is 100% efficient).
6. Explain how screws could be considered to be similar to inclined planes.
7. Describe the three classes of lever and give a practical example of each.
8. Explain how a jackscrew is used and how to calculate its ideal mechanical advantage.