Topic 10: Mechanical design
General Concepts

10.1.1 Define mechanical advantage, velocity ratio and efficiency.

**Mechanical advantage**
This is the factor that the machine multiplies the force put into it

**Velocity ratio**
A measurement of force amplification

**Efficiency**
Mechanical efficiency is the effectiveness of a simple machine

10.1.2 Calculate mechanical advantage (MA), velocity ratio (VR) and efficiency for simple mechanical systems.

\[ \text{MA} = \frac{\text{load}}{\text{effort}} \]
\[ \text{VR} = \frac{\text{distance moved by effort}}{\text{distance moved by load}} \]
\[ \text{Efficiency} = \frac{\text{MA}}{\text{VR}} \]

**Levers**

10.1.3 Describe first-, second- and third-class levers.

Identify load (L), effort (E) and fulcrum (F) in first-class levers (E–F–L, for example, see-saw, crowbar, scissors), second-class levers (E–L–F, for example, wheelbarrow, bottle opener, nutcracker) and third-class levers (L–E–F, for example, tweezers, broom, fishing rod).

The most common types of lever are Class 1 and Class 2 because they give you a Mechanical Advantage. This means you can move a large load using a small effort. The mechanical advantage of the Class 1 lever shown below is found by comparing the weight of the load with the effort needed to move it. Class 3 levers are used less often because their mechanical advantage is less than 1. This means the force needed to use them is greater than the force they can move.

10.1.4 Discuss the relevant efficiencies of the three classes of lever.

A good example of lever efficiency can be found here: [http://www.btinternet.com/~hognosesam/gcse/page55.html](http://www.btinternet.com/~hognosesam/gcse/page55.html)

**Mechanical Advantage of Levers**

We use simple machines, like levers, to make tasks easier. While the output work (work done by the machine) of a simple machine can never be greater than the input work (work put into the machine), a simple machine can multiply input forces OR multiply input distances (but never both at the same time).
The general formula for the mechanical advantage (MA) of levers:

\[ \text{MA lever} = \frac{F_o (\text{output force})}{F_i (\text{input force})} \]

Or you can use the ratio of the input arm length to the output arm length:

\[ \text{MA lever} = \frac{L_i \text{ (length of input arm)}}{L_o \text{ (length of output arm)}} \]

Most of the time, levers are used to multiply force to lift heavy objects.

**Example 1:** A construction worker uses a board and log as a lever to lift a heavy rock. If the input arm is 3 meters long and the output arm is 0.75 meters long, what is the mechanical advantage of the lever?

\[ \text{MA} = \frac{3 \text{ meters}}{0.75 \text{ meter}} = 4 \]

**Example 2:** Sometimes levers are used to multiply distance. For a broom, your upper hand is the fulcrum and your lower hand provides the input force. Notice the input arm is shorter than the output arm. The mechanical advantage of this broom is:

\[ \text{MA} = \frac{0.3 \text{ meter}}{1.2 \text{ meters}} = 0.25 \]

A mechanical advantage less than one doesn’t mean a machine isn’t useful. It just means that instead of multiplying force, the machine multiplies distance. A broom doesn’t push the dust with as much force as you use to push the broom, but a small movement of your arm pushes the dust a large distance.

10.1.5 Explain that, when a lever is in equilibrium, the net moment is zero.

A lever is in equilibrium when the effort and the load balance each other. The law of equilibrium is: The effort multiplied by its distance from the fulcrum equals the load multiplied by its distance from the fulcrum. This law of equilibrium is true for all classes of levers.
For example, 2 pounds of effort exerted 4 feet from the fulcrum will lift 8 pounds located 1 foot on the other side of fulcrum, as shown below. This effort times distance about the fulcrum is the torque, the rotational force referred to in the gears (wheel and axle) tutorial.

10.1.6 Calculate mechanical advantage and effort for first-, second- and third-class levers.

See activity worksheet

Gears

10.1.7 Describe gear systems.

Gears consist of toothed wheels fixed to shafts. The teeth interlock with each other, and as the first shaft (the driver shaft) rotates, the motion is transmitted to the second or driven shaft. The motion output at the driven shaft will be different from the motion input at the driver shaft - in place, speed, direction and other ways.

A number of gears connected together are called a gear train. The input (eg a motor) is connected to the driver gear. The output, (eg the wheel of a buggy) is connected to the driven gear.

Spur gears

The photograph below shows a simple gear train made up of a couple of spur gears. These are the common gears (or cogs) that look like wheels with teeth around the rim. Next to the photo is a diagram showing how you would draw this gear train in an exam.

In the drawing, the centre of each gear is shown by a cross. Each gear is drawn as two circles, one slightly larger than the other to show where the teeth would be. Teeth do not have to be drawn, but the number of teeth is written next to the gear, in this case 60 teeth and 15 teeth. Arrows indicate the direction that the gears are moving. Note that with two connected gears, they will be rotating in opposite directions.

10.1.8 Calculate velocity ratio for gear systems.

Gear ratio and output speed

Where there are two gears of different sizes, the smaller gear will rotate faster than the larger gear. The difference between these two speeds is called the velocity ratio, or the gear ratio, and can be calculated using the number of teeth. The formula is:

\[
\text{Gear ratio} = \frac{\text{number or teeth on driven gear}}{\text{number of teeth on the driver gear}}
\]

So the gear ratio for the simple gear train above, if the smaller gear is the driver gear, is:

\[
\text{Gear ratio} = \frac{60}{15} = 4.
\]

In other words, the driver gear revolves four times to make the driven gear revolve once.

If you know the gear ratio, and the speed input at the driver gear, you can calculate the speed output at the driven gear using the formula:

\[
\text{Output speed} = \frac{\text{input speed}}{\text{gear ratio}}
\]
So if the gear ratio is 4 and the driver gear is revolving at 200 rpm then the output speed = 200 ÷ 4 = 50 rpm

10.1.9 Describe the function of different types of gears in a range of objects.

Use rack-and-pinion, bevel and worm gears.

**Compound gear train**

Where very large speed reductions are required, several pairs of gears can be used in a compound gear train. A small gear drives a large gear. The large gear has a smaller gear on the same shaft. This smaller gear drives a large gear. With each transfer, the speed is significantly reduced.

**Worm gears**

Another method of making large speed reductions is to use a worm gear. This is a shaft with a thread like a screw. This connects at 90° to a large gear (the thread shaft points along the outside edge of the larger gear). Each time the shaft spins one revolution, the gear turns forward by only one tooth. If the gear has 50 teeth, this creates a gear ratio of 50:1. The worm can drive the worm gear round, but the worm gear cannot drive the worm. This means that worm gears are good to use in hoists, the load will not fall back when the motor stops. Worm gears are a good option when you wish to alter direction or rotary motion through 90° and reduce the speed. The photograph to the left shows a worm gear powered by a motor.

**Bevel gears**

Bevel gears, like worm gears, change the axis of rotation through 90°. The teeth have been specially cut so the gears will mesh at right-angles to each other, where spur gears must be parallel.

**Rack and pinion**

A pinion is a round cog and the rack is a flat bar with teeth. The driver cog either moves along the rack, as in a rack and pinion (funicular) railway - or else the driver cog moves the rack, as in the steering system in cars. Rack and pinion changes rotary motion into linear.

10.1.10 Explain a design context in which a compound rather than a simple gear train would be appropriate.
Consider the gearing system on a metal lathe designed to be changed to cut a specific type of thread. Consider ratios, mechanical advantage and changes.

10.1.11 Discuss the function of different types of gears in a range of objects. Use rack-and-pinion, bevel and worm gears.

<table>
<thead>
<tr>
<th>Car gearing system</th>
<th>Rack and Pinion</th>
<th>Worm gear</th>
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Belts

10.1.12 Describe a belt or chain drive system.

Consider profile, load, changes in load, and speed.

Pulley systems

Pulleys are used to change the speed, direction of rotation, or turning force or torque.

A **pulley system** consists of two **pulley wheels** each on a shaft, connected by a **belt**. This transmits rotary motion and force from the input, or driver shaft, to the output, or driven shaft. The diagram below shows a simple system comprised of two pulley wheels and a belt. It is a simple mechanical device to winch up and down a rope. When the motor is turned on it revolves the driver pulley wheel. The belt causes the driven pulley wheel to rotate as well, winding out the rope.

Pulley wheels are grooved so that the belt cannot slip off. Also, the belt is pulled tight between the two pulley wheels (in tension). The friction caused by this means that when the driver rotates the driven follows. Most pulley wheels have a central shaft on which they rotate. To keep the wheel firmly attached to the shaft it is usual to use what is called a ‘key’.

The diagrams to the left shows a keyed shaft which is pushed through the centre of the pulley wheel. A small rectangular key is then ‘tapped’ into position, holding the shaft and the pulley wheel together. This fitting means that the pulley wheel cannot slip on the shaft.
Chain and sprocket

A chain and sprocket changes \textit{rotary motion to linear motion} - or vice versa. A wheel-and-axle, rack-and-pinion, rope-and-pulley, screw thread, or chain-and-sprocket could also be used for this.

10.1.13 Calculate velocity ratio for belt or chain drive systems.

Image shows a pulley system consisting of two pulley wheels and a belt. The smaller, driver, pulley is 40mm wide and the larger, driven pulley is 120mm wide. The speed of the smaller wheel is 100rpm.

If the pulley wheels are different sizes, the smaller one will spin faster than the larger one. The difference in speed is called the \textit{velocity ratio}. This is calculated using the formula:

\[
\text{Velocity ratio} = \frac{\text{diameter of the driven pulley}}{\text{diameter of the driver pulley}}
\]

If you know the velocity ratio and the input speed of a pulley system, you can calculate the output speed using the formula:

\[
\text{Output speed} = \frac{\text{input speed}}{\text{velocity ratio}}
\]

Worked example

- Work out the velocity ratio and the output speed of the pulley shown in the diagram above.
- Velocity ratio \(= 120\text{mm} \div 40\text{mm} = 3\)
- Output speed \(= 100\text{rpm} \div 3 = 33.3 \text{rpm}\)

Torque

The velocity ratio of a pulley system also determines the amount of turning force or torque transmitted from the driver pulley to the driven pulley. The formula is:

\[
\text{output torque} = \text{input torque} \times \text{velocity ratio}.
\]

Pulley drive belts

Drive belts are usually made of synthetic fibres such as neoprene and polyurethane, with a V-shaped cross section. It is possible to reverse the direction of the driven pulley by twisting the belt as it crosses from input to output. Pulley belts have the advantage over chains that they do not need lubrication (though unlike a chain, a belt can slip).

10.1.14 Compare belt or chain drives and gear systems.

Consider profile, load, changes in load, and speed.

Drive chains are similar to drive belts in many ways, and which device is used is subject to several design tradeoffs. Drive chains are most often made of metal, while belts are often rubber, plastic, or other substances. This makes drive chains heavier, so more of the work put into the system goes into moving a chain versus moving a belt. On the other
hand, well-made chains are often stronger than belts. Also, drive belts can often slip (unless they have teeth) which means that the output side may not rotate at a precise speed, and some work gets lost to the friction of the belt against its rollers.

Teeth on toothed drive belts generally wear faster than links on chains, but wear on rubber or plastic belts and their teeth is often easier to observe; you can often tell a belt is wearing out and about to break more easily than a chain. Chains often last longer.

Chains are often narrower than belts, and this can make it easier to shift them to larger or smaller gears in order to vary the gear ratio. Multi-speed bicycles with derailleur s make use of this. Also, the more positive meshing of a chain can make it easier to build gears that can increase or shrink in diameter, again altering the gear ratio.

**chain drive versus gears**

- **Chain Drive** is light, highly efficient, inexpensive, and allows you to relatively easily change your motorcycle's final drive ratio. However, it requires regular lubrication, cleaning, and tension adjustment.
- **Shaft Drive** is heavier, almost but not quite as efficient, somewhat expensive, and makes it impractical to change the final drive ratio. However, the maintenance intervals are much farther apart.

10.1.15 Design a system to provide belt torsion to a belt-and-pulley system.

See activities workbook.

**Inclined plane**

10.1.18 Describe an inclined plane.

Consider inclined planes, screw threads and wedges.

An inclined plane is a surface where there is a **slope** on the end points, or in other words on a surface where the height is different. It is one of the six simple mechanisms. We all know that work done is force and distance, and by moving an object gradually on an inclined plane, less force is needed than lifting it up vertically.

An inclined plane can be used in many ways to make a job easier. In the simple example shown above, the load can be raised to the top either by pulling it up the slope or by lifting it vertically.

Screw threads make use of the inclined plane principle. The diagrams show how by
wrapping an inclined plane around a cylinder you get the **helix** form as on a screw thread. The threads are used in several different ways:
- To provide powerful movements (car jacks)
- To hold things in place (bolts and screws)
- To position things accurately (binoculars)

**Wedges**

When cutting hard materials, you can of course choose to crush it. However, to gain more precision and using less effort, a wedge can be used. Saws and wedges transfer the circular or linear motions of such inclined planes to the surface being cut and multiply the force being applied. The action of hammering the wedge into the stone with a linear action forces the inclined planes of the wedge sides to push the material apart. The force applied by hammering the wedge in is multiplied by the small surface point and inclined planes.

10.1.19 **Explain the advantage of an inclined plane.**

One famous use of inclined planes is the building of the pyramids. It is believed that the Egyptians used slopes to lower the force needed to move the huge rock blocks. It transfers horizontal forces eventually into vertical forces in the sacrifice of a longer distance needed. The mechanical advantage is also very high as it can be adjusted to the needs.

An inclined plane makes doing work easier by changing both the direction and the amount of effort that are used to lift an object. Work, in physics, is defined as the amount of force applied to an object multiplied by the distance over which the force is applied. Mathematically, this can be expressed by the following equation:

\[ \text{Work} = \text{Force} \times \text{Distance} \]

**Mechanical advantage of an inclined plane**

The mechanical advantage (M.A.) of an inclined plane is the length of the incline divided by its height. The longer the incline the greater the mechanical advantage. That means the longer the incline the less force or effort needed to move an object up the incline.

\[ \text{M.A.} = \frac{\text{Length}}{\text{Height}} \]

**Example:** A man is using an 8 metre board to slide things into the back of his truck. The truck is 1 metre from the ground. What is the mechanical advantage of this incline?

**Solution:**
- Length of incline = 8 metre
- Height of incline = 1 metre
M.A. = 8 m. / 1 m.
M.A. = 8

This means the effort is multiplied by 8 when using this inclined plane or the total weight of an object is divided by 8 to find the force required to lift the object.

The mechanical advantage of a screw can be calculated by dividing the circumference by the pitch of the screw.
Pitch equals 1/ number of turns per inch.
This would give you ideal mechanical advantage and would not take into account friction and other forces.

A formula for calculating work is

\[ W = F \cdot d \]

where \( W \) = work (in N•m), \( F \) = force (in N), and \( d \) = distance (in m). Use this formula to calculate work done using the inclined plane. Here, \( F \) = the average force needed to pull the block up the inclined plane and \( d \) = the length of the inclined plane.

A formula for calculating the efficiency of a machine is

\[ \text{efficiency} = \frac{\text{work output}}{\text{work input}} \times 100 \]
## 10.2 Mechanical motion

### 10.2.1 Describe linear, rotary, intermittent, oscillating, reciprocating and irregular motion.

**Linear Motion**  
Linear motion is motion in a straight line. Steady linear motion is known as velocity (uniform motion in a straight line). An example of linear motion is the cutting arm of a paper guillotine (photo below) as it travels from one side of the machine to the other.

**Rotary Motion**  
Motion in a circle is called rotary motion. The number of complete revolutions made per minute (rpm), is called rotary velocity.

**Intermittent Motion**  
Intermittent motion is motion which starts and stops regularly. For example, in a cinema projector the film needs to be moved on one frame at a time then held stationary while the light projects it onto the screen. This is usually done with a Geneva stop as shown here. Intermittent motion is usually the end result of a mechanism rather than the starting point for conversion. [http://www.flying-pig.co.uk/mechanisms/pages/intermittent.html](http://www.flying-pig.co.uk/mechanisms/pages/intermittent.html)

**Oscillating Motion**  
Oscillating motion is motion backwards and forwards in a circular arc. E.g. playground swings (photo) and clock pendulums.

**Reciprocating Motion**  
Reciprocating motion is linear motion backwards and forwards in a straight line. Sewing machines make use of this type of motion. Jigsaws and scroll saws which are often used in school workshops have blades that cut by reciprocating motion.
10.2.2 Explain how linkages can be used to change the direction of motion of components.

10.2.3 Discuss mechanical motion in a range of contexts.
Consider a hydraulic digger, a bicycle, a car jack and a hand drill.

10.2.4 Define torque.

10.2.5 Discuss the design features of a ratchet and pawl system.

10.2.6 Describe simple cam shapes and their advantages.

9.2.7 Identify cam followers and state their use.

9.2.8 Explain the use of a series of cam and follower mechanisms to achieve a set purpose.

This can be explored in a number of ways: using Lego, paper and pins, or through virtual online models.

10.3 Conversion of motion

10.3.1 Identify how mechanisms allow conversion of one form of motion to another.

For example, rack and pinion, bell cranks, toggle clamps, linkages and levers.

10.3.2 Identify the mechanisms in a bicycle.

Consider chain drive, levers, linkages and gears.

10.3.3 Design combinations of mechanisms to achieve specific tasks.

Consider the following tasks:
• alter the axis of rotation
• change the type of movement
• increase force and decrease speed
• decrease force and increase speed.

10.3.4 Discuss how designers make use of simple mechanisms in the home.

Consider water tap, garlic crusher and foot operated trash/rubbish bin.

10.3.8 Evaluate the importance of strength and stiffness in a design context.

The six simple machines are the primary machines that can be found in even the most complex machines. The 6 simple machines are:

**The Pulley** - This simple machine reverses the direction of a force, and when multiple pulleys are utilized in conjunction with each other, less force is required to lift an object. The one downside of using multiple pulleys is that the rope’s end must move across a longer distance than the object being lifted.

**The Wheel and Axle** - This machine is setup such that the axle is connected to the center of the wheel. This setup allows the wheel to be thereby be set in motion once the axle starts to turn.

**The Lever** - This simple machine is such that when downward motion is applied at one end, upward motion is created at the other end.

**The Inclined Plane** - This simple machine allows for an object to be moved vertically without being lifted.
**The Wedge** - This simple machine allows motion from objects such as hammers to be transferred into a breaking, cutting, or splitting motion. The wedge is a key machine used in machines that cut or break objects.

**The Screw** - This simple machine is crafted in such a fashion to where a groove that wraps around a central material in the shape of a spiral. When placed into a slot that fits the screw's groove and shape, this allows for rotary motion to be converted into forward or backward motion.