CAIE Physics IGCSE

Topic 1: Motion, Forces and Energy

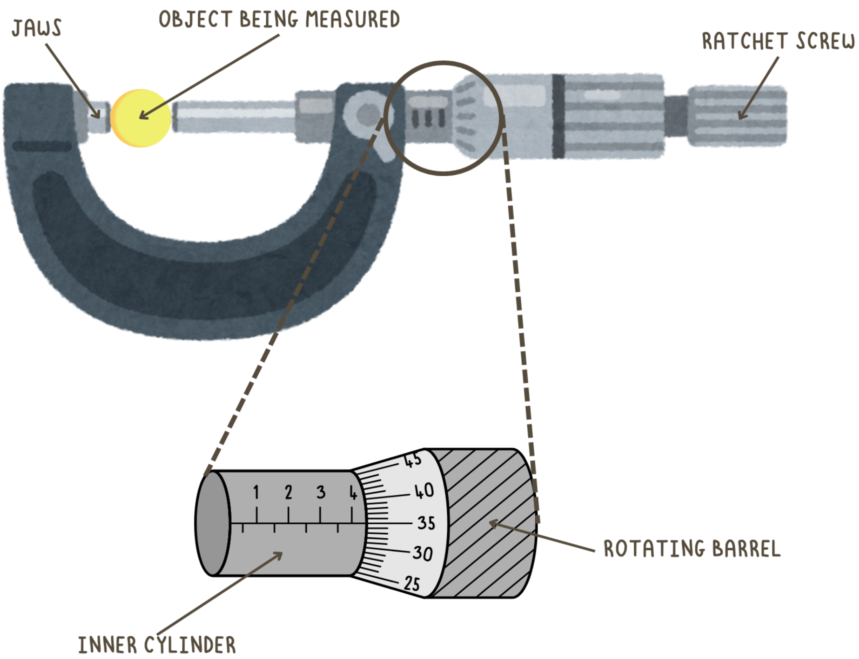
Summary Notes

*Definitions in **bold** are for extended students only*

1.1 Physical quantities and measurement techniques

Measurement techniques:

- A ruler (rule) is used to measure the length of an object between 1mm and 1m.
  - **A micrometer screw gauge is used to measure very small distances that a rule cannot measure.**



As you turn the screw, the gauge's jaws move to fit around your object. Its size can be read on the inner cylinder (which gives its integer value in mm) and the rotating barrel (which gives its decimal value to 0.01mm).

- A measuring cylinder is used to measure the volume of a liquid or an object that can sink. Placing the object into a measuring cylinder full of water causes the water level to rise. This rise is equal to the volume of the object.
  - For regular shaped solids, you can also find their volume by calculation.
- Clocks and timers (both analogue or digital) are used to measure time intervals.

To measure a short distance or time interval, an average value is calculated from multiple measurements. This reduces percentage uncertainty, which is higher for smaller measurements.

- This usually requires repeat measurements, but for the period of a pendulum, one measurement is taken for several oscillations and then a mean is calculated.

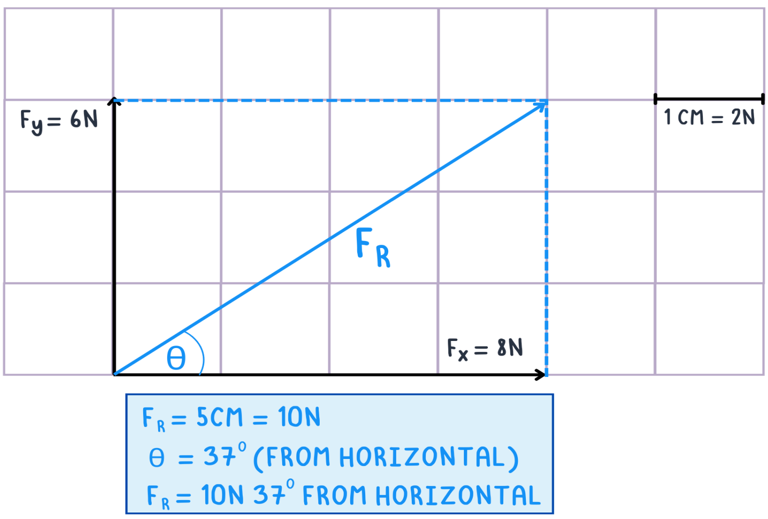
Physical quantities:

- A scalar quantity has magnitude only.
- A vector quantity has magnitude and direction. They can be represented by arrows.

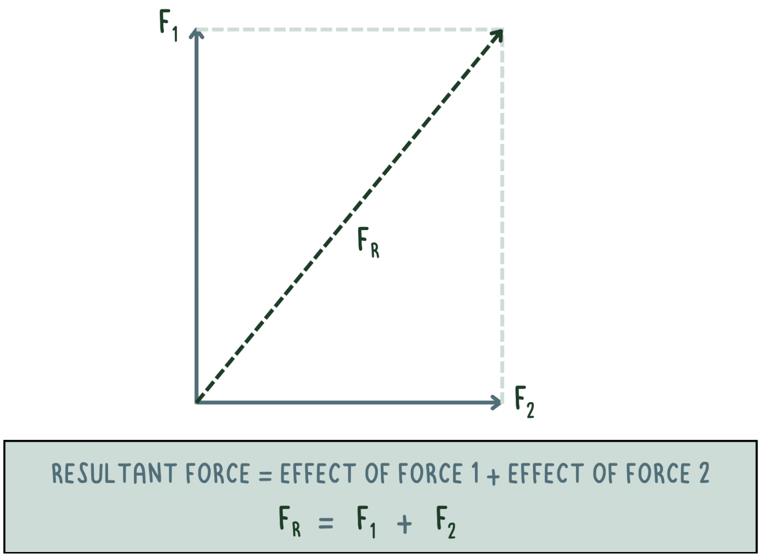
Scalar Examples	Vector Examples
Distance	Displacement
Speed	Velocity
Time	Acceleration
Mass	Momentum
Energy	Force
Temperature	Electrical/gravitational field strength

Vectors at right angles to one another can be combined into one resultant vector. This can be done for forces and velocities, either graphically or by calculation.

- Graphically, vectors are drawn to scale as arrows at right angles (length is their magnitude) so that a diagonal from their origin gives us the resultant.



- By calculation, the resultant's magnitude is found using Pythagoras' theorem ($a^2 + b^2 = c^2$), and its direction is found using trigonometry.



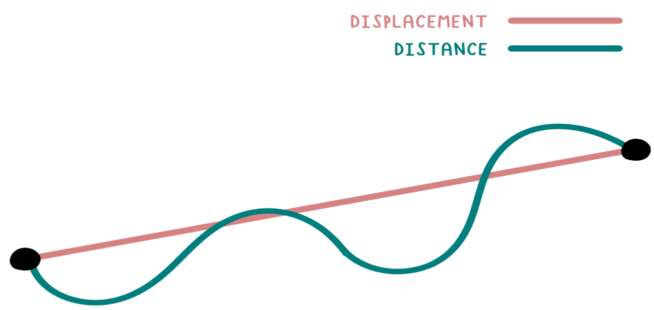
1.2 Motion

- Speed is defined as the distance travelled per unit time:

$$speed = \frac{distance\ travelled}{time} \quad units = m/s$$

- Velocity is the speed in a given direction:

$$velocity = \frac{displacement}{time} \quad v = \frac{s}{t} \quad units = m/s$$



- If speed is changing, an object is accelerating or decelerating.
  - In this case, the object's speed is calculated as an average:

$$average\ speed = \frac{total\ distance\ travelled}{total\ time} \quad units = m/s$$

  - **Acceleration is the rate of change of velocity:**

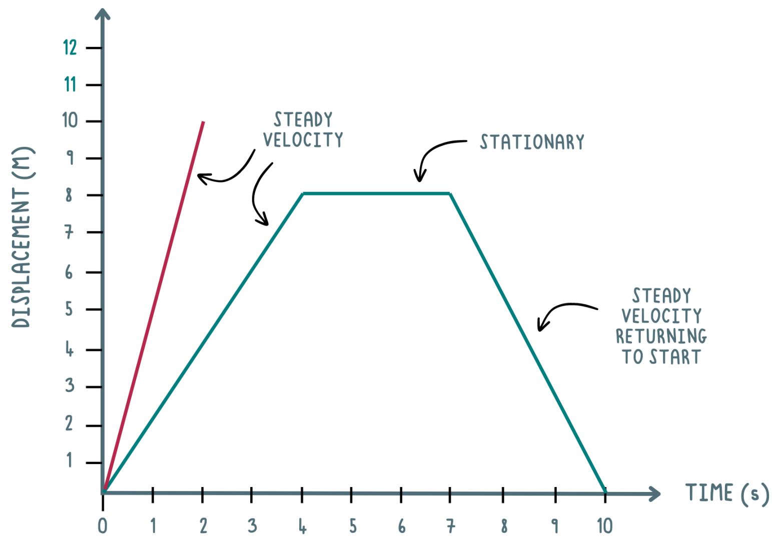
$$acceleration = \frac{change\ in\ velocity}{change\ in\ time} \quad a = \frac{\Delta v}{\Delta t} \quad \mathbf{units = m/s^2}$$

  - **Deceleration is a negative acceleration.**:

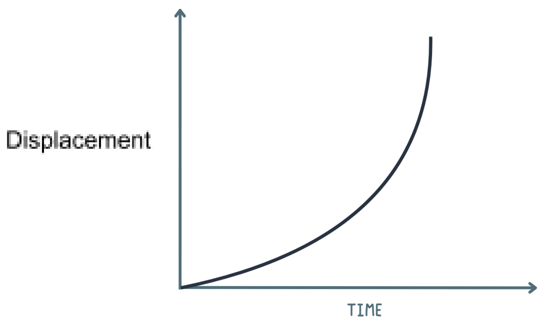
Before plugging any values into these speed, velocity, and **acceleration** equations, double-check all the units are equivalent to one another, and convert them if needed.

- Distance and displacement could be measured in mm, cm, m, or km.
- Time could be measured in ms, s, minutes, or hours.
- The answer is usually in metres and seconds.

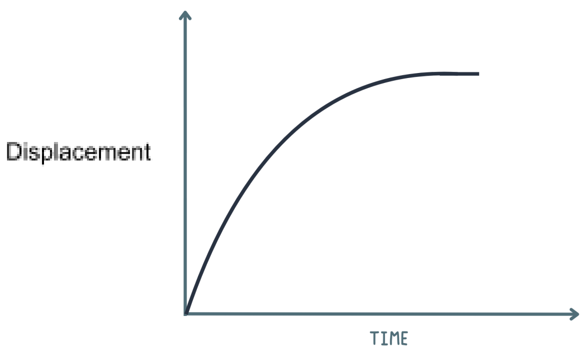
Interpreting a displacement-time graph:



- The gradient is the velocity (or the speed on a distance time graph).
  - The object is at rest when the gradient is horizontal.
  - The object is moving at a constant speed/velocity when the gradient is straight.
  - The object is accelerating when the line is curved and the gradient is increasing.



  - The object is decelerating when the line is curved and gradient is decreasing.

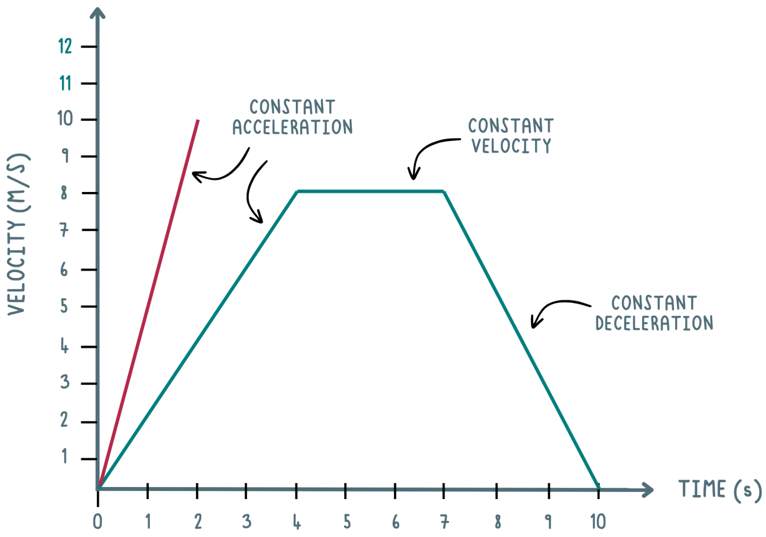


  - A negative gradient shows the object is returning to the starting point.
  - To calculate speed/ velocity:

$$speed\ or\ velocity\ =\ gradient\ =\ \frac{change\ in\ Y}{change\ in\ x}$$

(If calculated for a curved section, the answer is the average speed.)

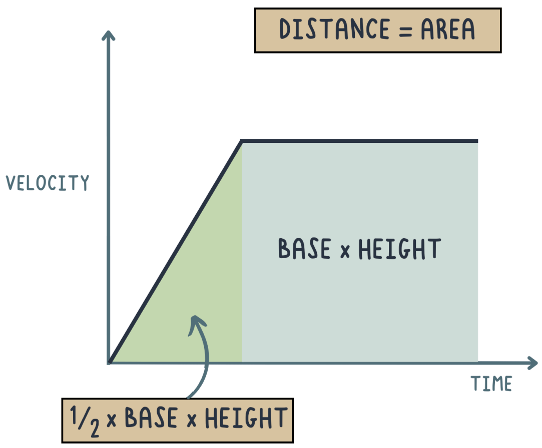
Interpreting a velocity-time graph:



- The gradient is acceleration.
    - The object is at rest when the speed/ velocity is zero.
    - The object is moving at a constant speed when the line is horizontal.
    - The object is accelerating when the line has a positive gradient.
    - The object is decelerating when the line has a negative gradient.
    - **The object is moving with constant acceleration when the line is straight.**
    - **The object is moving with changing acceleration when the line is curved.**
    - **To calculate the acceleration:**

$$acceleration = gradient = \frac{change\ in\ y}{change\ in\ x}$$

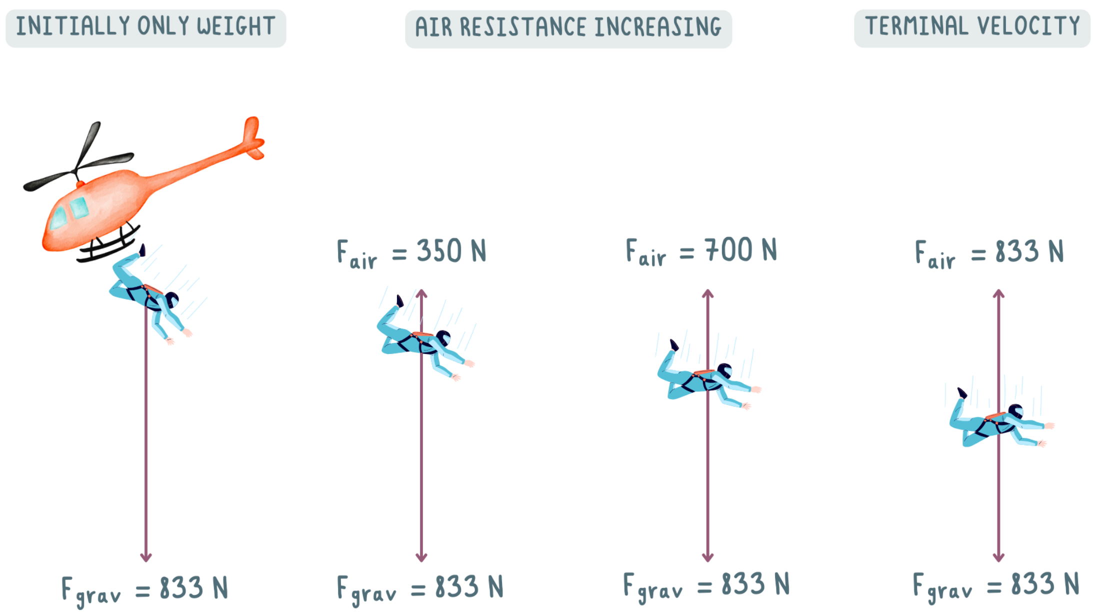
- The area under the graph gives the distance travelled.
    - To calculate the area under the graph, split it into rectangles and triangles:



The motion of objects falling:

- Objects in free fall, near the Earth's surface, all will fall with an approximately constant acceleration of free fall known as 'g'.

  g = approximately $9.8 m/s^2$.
- **Objects free falling in a uniform gravitational field are in the absence of air/liquid resistance and all fall with this same constant acceleration ($9.8 m/s^2$).**
- **Objects falling in a uniform gravitational field in the presence of air/liquid resistance, fall with decreasing acceleration.**
  - **Initially, there is no air resistance and the only force at work is weight. At this point, acceleration is $9.8 m/s^2$ (g).**
  - **As it accelerates, speed increases, which increases air resistance.**
  - **This decreases the resultant force (downwards), so acceleration decreases.**
  - **Eventually, weight and air resistance are equal and opposite, so there is no resultant force, no acceleration, and the terminal velocity is reached.**



1.3 Mass and weight

- Mass measures how much matter is in an object (when the object is at rest relative to the observer). $units = kg$
- Weight is the gravitational force that acts on objects with mass. $units = Newtons\ (N)$
- Gravitational field strength (g) is the amount of gravitational force (weight) acting on an object, per unit of its mass.

$$gravitational\ field\ strength = \frac{weight}{mass} \quad g = \frac{W}{m} \quad units = N/kg$$

  - Both gravitational field strength and acceleration of free fall are represented by 'g' because they are equivalents (9.8N/kg and 9.8m/s^2, respectively, on Earth).
  - **As shown in the equation, weight is the effect of the gravitational field on a mass. Therefore, as the value of 'g' differs from planet to planet, an object's weight differs from planet to planet too. An object's mass, however, remains the same.**

The weight and mass of two different objects can be compared using a balance. This is possible because 'g' is a constant on Earth.

1.4 Density

- Density is the mass per unit volume of an object:

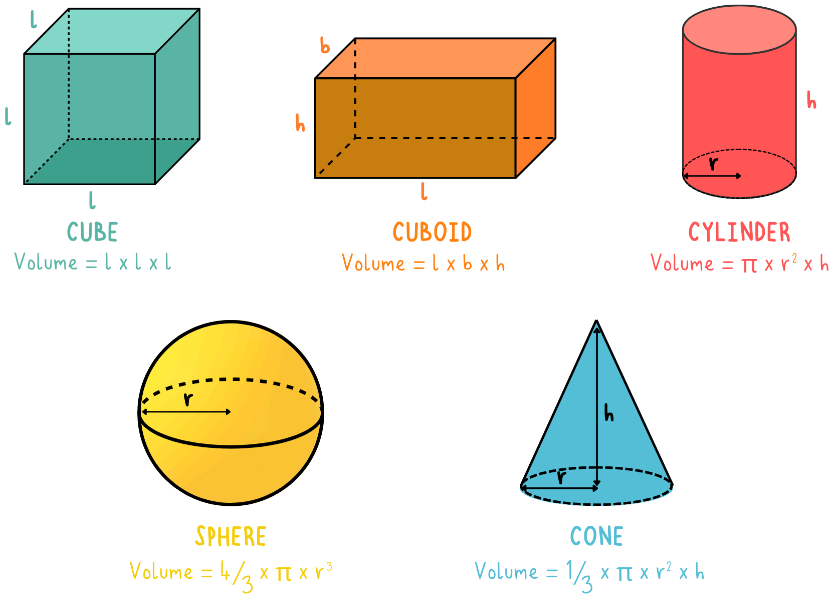
$$density = \frac{mass}{volume} \quad \rho = \frac{m}{V} \quad units = kg/m^3$$

To find the density of a liquid:

- Calculate the mass - mass is equal to the difference in mass of a measuring cylinder when empty and after filling it with the liquid, measured using a balance.
  $liquid's\ mass = mass\ of\ cylinder\ full\ of\ water - mass\ of\ empty\ cylinder$
- Measure the volume - volume is read from the cylinder.
- Calculate the density by plugging mass and volume into the density equation.

To find the density of a solid:

- Measure the mass - mass is measured using a balance.
- Calculate the volume:
  - Of regularly shaped solids - volume is found by measuring the solid's dimensions and using the appropriate equation for the object's shape:



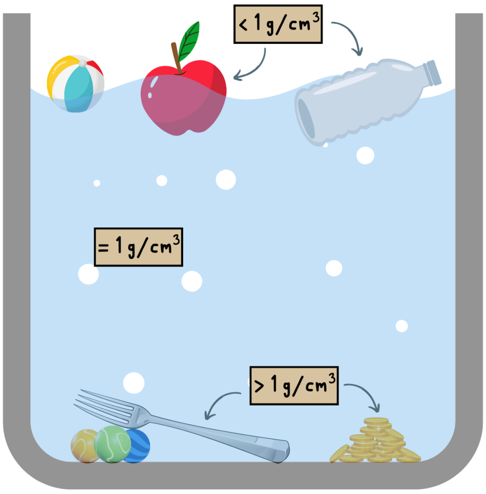
- Of irregularly shaped solids - volume is equal to the rise in water when the object is placed into a measuring cylinder full of water (volume by displacement)(see 1.1).

$$solid's\ volume\ = water's\ volume\ \ in\ cylinder\ with\ object\ - water's\ volume\ in\ cylinder\ without\ object$$

- Calculate the density by plugging mass and volume into the equation.

An object will float if it is less dense than the liquid it is placed in and sink if it is more dense than the liquid it is placed in.

- Density of water is 1g/cm^3; objects with density greater than this sink in water - those with a density less than 1g/cm^3, float.



- **The same is true for two liquids (if they do not mix): one liquid will float because it is less dense than the other liquid.**

1.5 Forces

1.5.1 Effects of forces

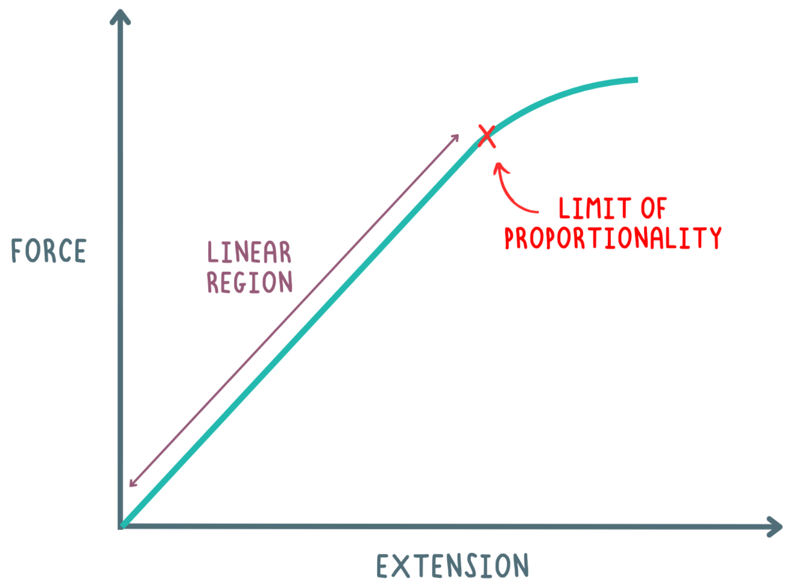
Forces can change the size and shape of an object:

Elastic solids can be extended when force is applied and will return to their original shape and size when the force is removed.

- **The spring constant is the force required per unit of extension:**

  $spring\ constant = \frac{force\ applied}{extension}$ $k = \frac{F}{x}$ $units = N/m$ (Hooke's Law)

- The extension of an object can be investigated experimentally:
  - The initial length of an object is measured with a ruler.
  - Masses are attached to the object incrementally (adding force), and the object's length is measured and recorded after the addition of each.
  - The extension is found by subtracting the initial length from the new length.
  - The experiment is repeated 3 times and an average extension found for each mass.
  - The force is weight, so can be found by multiplying mass by the gravitational field strength 9.8N/kg (see 1.3).
  - Force and extension are plotted on a load-extension graph:

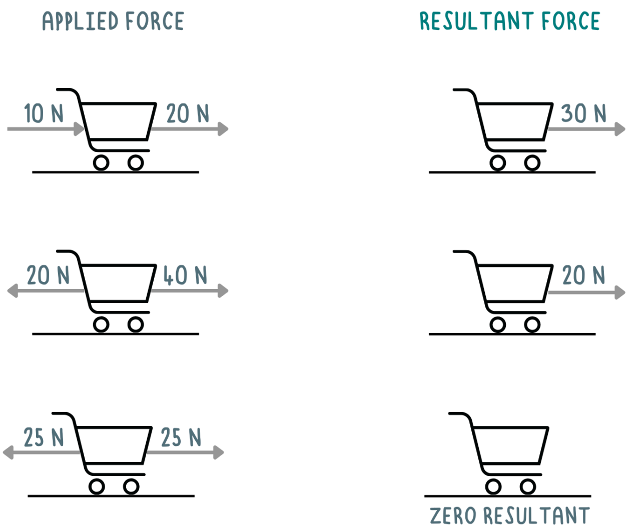


- Load-extension graphs for an elastic object should be linear and pass through the origin.
  - **The gradient of the linear section is the spring constant, k.**
  - **The point where the graph stops being linear is the limit of proportionality. Beyond which, $k = \frac{F}{x}$ is no longer true, and an object stretches irreversibly.**

Forces can change the speed or direction of an object:

- A resultant force is a single force that describes the combined action of all forces acting on an object.
  - **The resultant of forces at right angles to one another can be found (see Topic 1.1).**
  - The resultant of forces acting along the same straight line can be found by:

$$sum\ of\ all\ forces\ acting\ in\ one\ direction\ -\ sum\ of\ those\ acting\ in\ the\ opposite\ direction$$

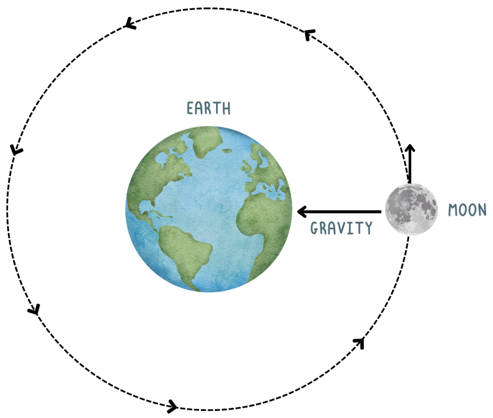


If forces balance one another out when combined, there is no resultant force.

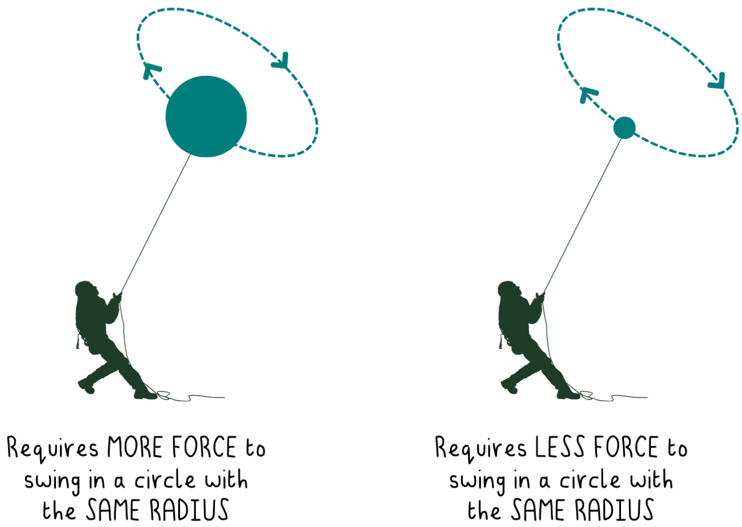
- Without a resultant force, an object either remains at rest or continues in a straight line at a constant velocity. *(Newton's First Law)*
- With a resultant force, an object's velocity will change (acceleration) either by changing speed or direction of motion.
- **The acceleration of an object is proportional to the resultant force acting on it and inversely proportional to the object's mass. Where force and acceleration act in the same direction:**

$$force\ =\ mass \times acceleration \qquad F\ =\ ma \qquad (Newton's\ Second\ Law)$$

- **To move in a circular motion, a resultant force is needed.**
    - **Objects moving in a circle are always changing direction (so velocity is always changing).**
    - **This requires a force to continually act perpendicular to the object's direction of motion (eg. the force of gravity on something orbiting Earth).**



    - **If mass and radius are constant, when force increases, speed increases.**
    - **If mass and speed are constant, when force increases, radius decreases.**
    - **To keep speed and radius constant in the case that mass increases, an increased force is required.**



Friction:

- Friction (drag) is a force between two surfaces which can impede motion and result in heating.
    - It can act on an object moving through liquid or gas (e.g. air resistance).

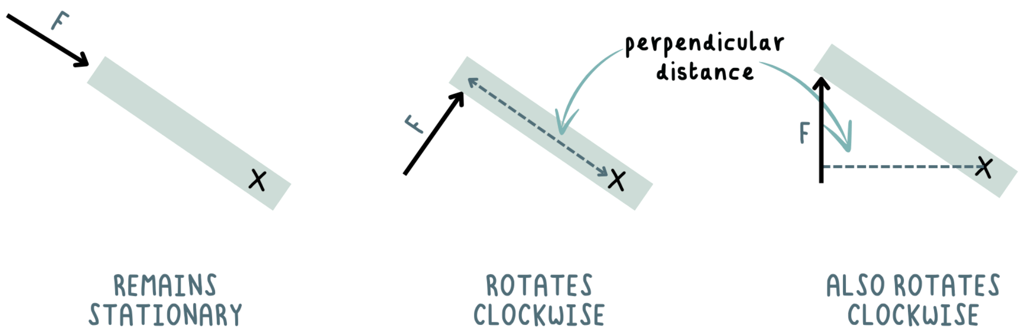
1.5.2 Turning effect of forces

- The pivot point is the point which the object can rotate about.

If a force is applied in the same line as the pivot the object will not rotate, and remains stationary.

If the force applied is in a different line to the pivot, it will rotate in the direction of the force.

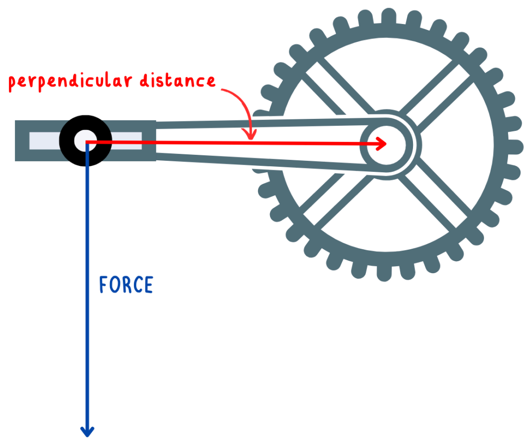
- If perpendicular to the object, perpendicular distance is the length of the object.
- If not perpendicular to the object, perpendicular distance to the pivot is found using trigonometry .



- The moment of a force is a measure of its turning effect:

$$moment\ of\ a\ force = force \times perpendicular\ distance \quad moment = Fd$$

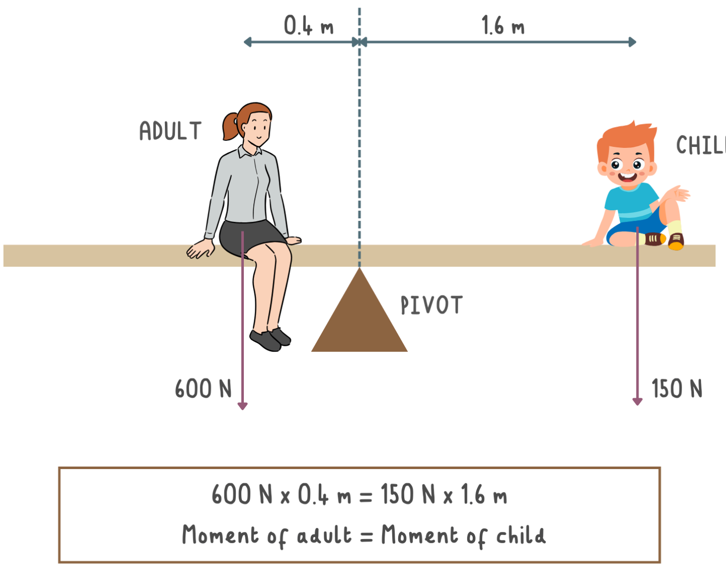
Example: A bike pedal - when riding a bike, pressing your foot down on the pedal causes a moment about the pivot, turning the pedal arms.



When there is force on either side of the pivot, the object will rotate about the pivot point in the direction of the force that creates a greater moment (either clockwise or anticlockwise).

- When the clockwise moment equals the anticlockwise moment there is no resultant force, no resultant moment, and the object is in equilibrium (balanced).

Example: A see-saw - when sat on a see-saw, the weight of each person causes a moment. The person that creates a larger moment, is lowered to the floor. If both people create equal moments, the see-saw is balanced.



When there is more than one force on either side of the pivot, the sum of the anticlockwise moments and the sum of all the clockwise moments are compared. Again, the object rotates in the direction of the forces creating a greater moment.

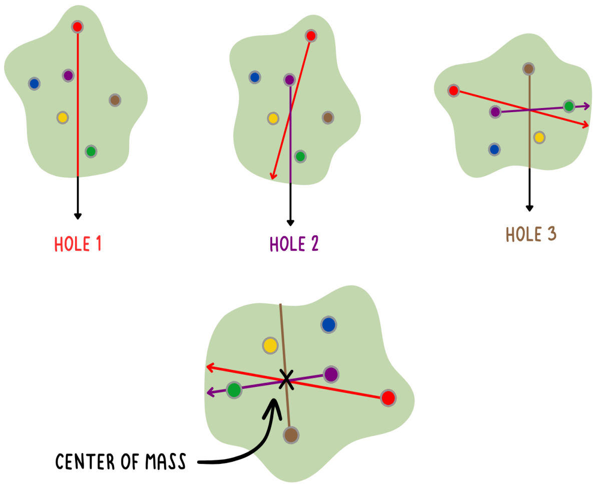
An experiment can be performed to show that there is no resultant moment on an object in equilibrium:

- **Pivot a uniform ruler at its centre**
- **Place different masses at different distances from the centre on either side until it balances**
- **Multiply the total mass on either side by 9.18N/kg (force of weight) to calculate anticlockwise and clockwise moments.**
- **The clockwise and anticlockwise moments will be equal.**

1.5.3 Centre of gravity

- The centre of gravity of a body is the point at which all of its weight can be considered to act.

To calculate the centre of gravity of an irregularly shaped plane lamina:
- Hang up the lamina and suspend a plumb line (thread) from the same place.
- Mark the position of the plumb line.
- Repeat with the lamina suspended from different places.
- Where these lines intersect is the centre of gravity.



The position of the centre of gravity affects the stability of simple objects:
- If the centre of mass is below the point of suspension of an object, it will be in stable equilibrium (e.g. a hanging plant pot).
- If the centre of mass is above the point of suspension of an object, it will be in unstable equilibrium (e.g. a pencil placed on its sharp end).
- If the line of action of the object's weight moves outside the base, there will be a resultant moment and it will topple.

So objects with a lower centre of gravity and a wider base are more stable.

1.6 Momentum

- **Momentum is the product of mass and velocity:**

$$momentum = mass \times velocity \quad p = mv \;\; units = kg\, m/s$$

- **Impulse is the product of force and time, equal to the change in momentum:**

$$impulse = force \;\; x\, time\, for\, which\, force\, acts = \Delta(mv) \qquad units = Ns$$

In a collision, momentum is always conserved (principle of the conservation of momentum).
The total momentum before is equal to the total momentum afterwards.

- **This can be used to solve problems in one dimension.**

Example:

- **A 10kg stationary gun is loaded with a 10g bullet. It is fired, with the bullet travelling at** $100ms^{-1}$**. What is the recoil speed of the gun?**

$$total\, momentum\, before = 0 \text{ kg m/s}$$
$$total\, momentum\, before = total\, momentum\, afterwards$$
$$\text{So change in momentum} = 0\ (\Delta(mv) = 0)$$
$$0\, kg\, m/s = 0.01kg \times 100ms^{-1} = 10v$$
$$v = -0.1ms^{-1}$$

The velocity is $-0.1ms^{-1}$, with the minus sign showing direction because it is a vector.
So the recoil speed is $0.1ms^{-1}$ **(the magnitude of the velocity vector only)**

1.7 Energy, work and power

1.7.1 Energy

Energy is stored in different forms including kinetic, gravitational potential, chemical, elastic (strain), nuclear, electrostatic and internal (thermal).

You can calculate kinetic and gravitational potential energy:

$$Kinetic\, energy = \frac{1}{2} x\, mass\, x\, (velocity)^2 \quad E_k = \frac{1}{2}mv^2$$
$$Gravitational\, potential\, energy = mass\, x\, gravitational\, field\, strength\, x\, height \quad E_p = mgh$$
$$\text{units} = \text{J}$$

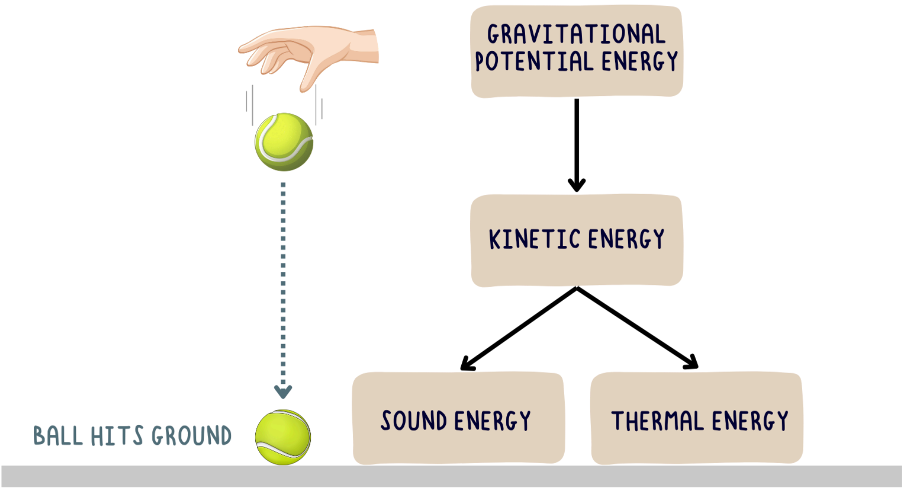
Energy can be transferred between the different forms (stores) during events and processes.
Energy can be transferred in various ways including:

- Forces e.g. when gravity accelerates an object downwards and gives it kinetic energy.
- Electrical currents e.g. when a current passes through a lamp and it emits light and heat.
- Heating e.g. when a fire is used to heat up an object.
- Waves (electromagnetic/ sound) e.g. vibrations cause waves to travel through air as sound.

Energy is always conserved. The total energy before is equal to the total energy after.

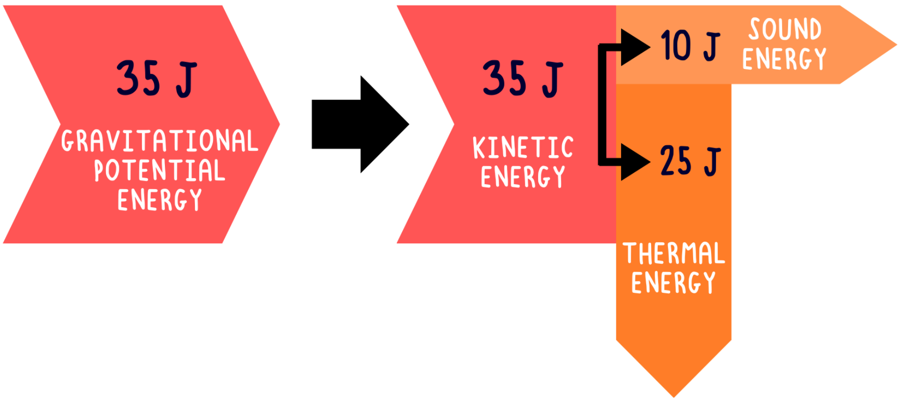
Example: When a ball is dropped, gravitational potential energy becomes kinetic energy as it accelerates downwards. Upon impact with the floor, this kinetic energy will become thermal energy and sound energy. The energy never ceases, it is transferred between forms.

Energy transfer can be shown using a flow diagram:



- The arrows show the direction of the energy transfer.
  - When there are multiple arrows originating from an energy store, it is being split to transfer into more than one energy type, totalling the original.

Energy transfer can also be shown using a Sankey diagram:



- **The arrows show the direction of the energy transfer.**
  - **The end of the arrow pointing to the right is useful energy output.**
  - **The end that points down is wasted energy.**
  - **The arrow width shows the amount of energy going to each store.**

The change in gravitational potential energy as you raise the ball can be calculated using:

$$change\ in\ gravitational\ potential\ energy\ =\ mass\ x\ gravitational\ field\ strength\ x\ change\ in\ height$$

$$\Delta E\,p\ =\ mg\Delta h$$

1.7.2 Work

Work done is equal to the energy transferred.

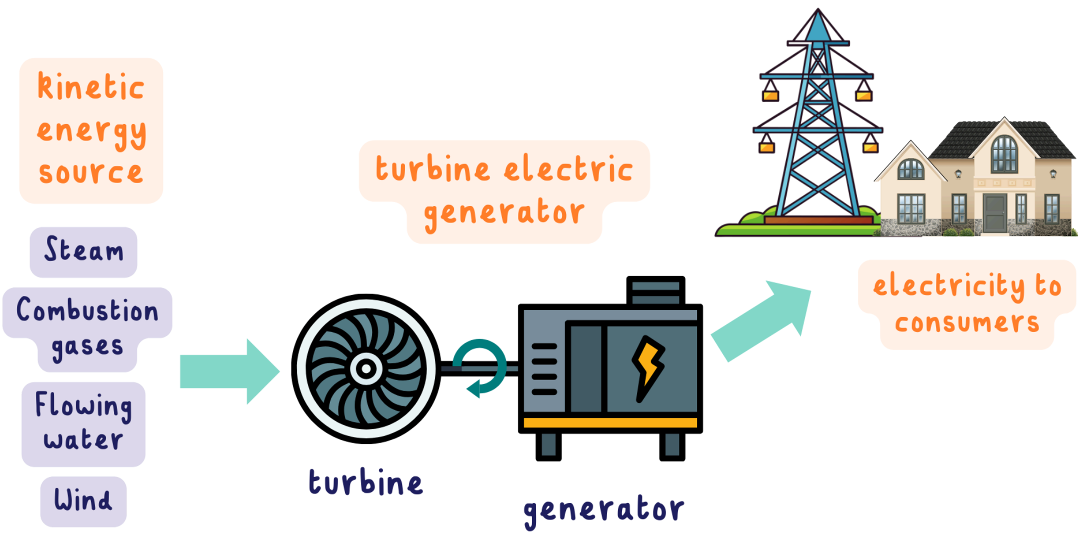
- Mechanical work is done when energy is transferred by a force, which moves something a distance.
- Electrical work is done when energy is transferred through electrical currents.

$$work\ done = force \times distance = energy\ transferred \quad W = Fd = \Delta E$$

1.7.3 Energy Resources

Energy can be used to generate electrical power:

- A turbine is turned using energy from an energy resource.
- The turbine turns coils, in a magnetic field, in a generator.
  - This generates electrical power.



The energy needed for this can be obtained from different resources. There are disadvantages and advantages of using each resource in terms of:

- Renewability - the ability to replenish energy as quickly as it is used.
- Availability - the ease of accessing the resource.
- Reliability - the ability to provide a consistent supply of energy.
- Scale - the amount of energy that can be produced using this resource.
- Environmental impact - the effects on the environment of obtaining and using the resource.

<u>Fossil fuels as an energy resource:</u>

Fossil fuels are a source of chemical energy. They are formed from the decomposition and compression of organism remains over millions of years.

Fossil fuels are burnt to generate electrical power:
- Their chemical energy is transferred to heat energy.
- The heat energy is used to boil water, creating steam.
- The steam turns the turbine.

Advantages	**Disadvantages**
• Reliable (they can be burnt on demand when needed). • Large-scale energy production. • Readily available (although resources are depleting).	• Non-renewable (because they take millions of years to form). • Releases greenhouse gases that cause global warming.

<u>Biofuels as an energy resource:</u>

Biofuels are another source of chemical energy. They are produced from plants and animal waste.

Like fossil fuels, they are burnt to generate electrical power:
- Their chemical energy is transferred to heat energy.
- The heat energy is used to boil water, creating steam.
- The steam turns a turbine.

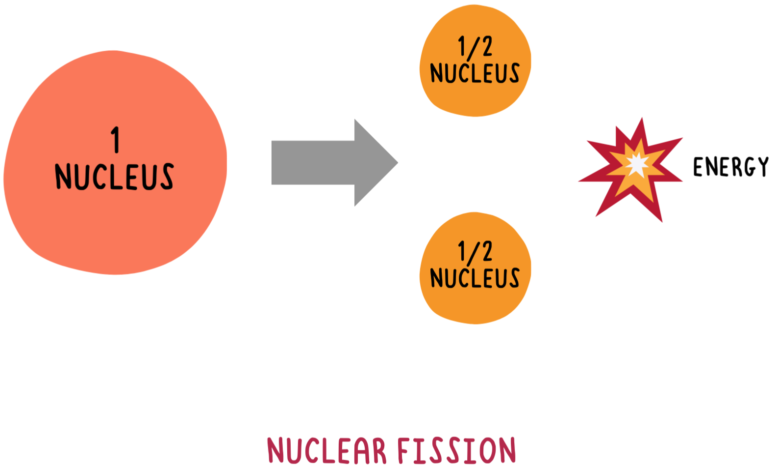
Advantages	**Disadvantages**
• Renewable (new plants can be grown and animals will always produce waste). • Reliable • Carbon neutral because carbon dioxide is released when biofuels are burnt, but used by the plants for photosynthesis.	• Availability is limited by the time, land and resources needed to grow plants.

Nuclear fuels as an energy resource:

Nuclear fuels are the nuclei of radioactive isotopes which release energy when split in two (**nuclear fission**). They are another non-renerable resource, so share many advantages and disadvantages with fossil fuels.

Nuclear fuels undergo nuclear fission to generate electrical power:

- Heat energy is released by nuclear fission.
- The heat energy is used to boil water, creating steam.
- The steam turns a turbine.



Advantages	Disadvantages
• Reliable (they can be used on demand when needed). • Large-scale energy production. • No pollution is released (unless radioactive waste isn't effectively stored).	• Non-renewable (the atoms used are in finite supply). • Availability is limited.

Water as an energy resource:

Water's waves and tides can generate electrical power:

- The kinetic energy as waves and tides move is used to turn underwater turbines.

Advantages	Disadvantages
• Renewable (water is not used up in the process). • No pollution is produced. • Reliable and available (there are always waves and tides).	• Destroys habitats. • Small-scale.

Water can also be released from behind hydroelectric dams to generate electrical power:

- The water behind the dam is above ground level, so has gravitational potential energy.
- This energy is transferred to kinetic energy when water is released down a slope.
- The flowing water turns the turbine.

Advantages	Disadvantages
• Reliable (water can be released on demand when needed). • Available (water is usually easy to access). • Large scale.	• Dam creation destroys habitats and greenhouse gases are produced to pump the water.

<u>Radioactive elements as an energy resource:</u>

Radioactive elements are a source of geothermal energy. They are found deep in the earth.

Decaying radioactive elements can be used to generate electricity:

- As radioactive elements decay, their geothermal energy heats the surrounding rock.
- Water is poured into shafts in the hot rock.
- The heat energy boils the water, creating steam, which is returned via another shaft.
- Steam turns a turbine.

Advantages	Disadvantages
• Renewable • Reliable	• Small-scale (as there are few suitable locations with radioactive elements). • Can release of greenhouse gases from underground.

<u>The Sun as an energy resource:</u>

The Sun's light (electromagnetic waves) can be used to generate electricity:

- Solar energy from sunlight is turned into an electrical current by solar cells.

The Sun's light can also be used to heat water:

- Infrared waves of the Sun's light heat water, contained within solar panels.
- The water goes to a tank and is stored for later use.
- A boiler may be needed to heat the water further.

The Sun heats the atmosphere, creating wind which can also generate electricity:

- As the wind blows, it transfers kinetic energy to the blades of wind turbines.

Advantages	Disadvantages
• Renewable • No greenhouse gases or pollution produced.	• Small-scale • Not reliable (relies on specific weather conditions of sun or wind).

The original source of energy for most energy resources is the sun, (apart from for geothermal, nuclear and tidal).

- **The sun's energy is released by nuclear fusion.**
- **Research is being done to investigate how nuclear fusion could be used to produce electrical energy on a large scale.**

Efficiency of an energy transfer:

As energy is transferred in an event or process, it spreads out between objects and surroundings.

The efficiency of an energy transfer measures how much of the total energy supplied is applied to useful work done.

- **Efficiency can be expressed as a percentage:**

$$percentage\ efficiency = \frac{useful\ energy\ output}{total\ energy\ input} x\ 100 = \frac{useful\ power\ output}{total\ power\ input}\ x\ 100$$

  - It can never exceed 100%, due to the conservation of energy.

1.7.4 Power

Power is the rate at which energy is transferred or the rate at which work is done.

$$power = \frac{energy\ transferred}{time} \quad P = \frac{\Delta E}{t} \qquad power = \frac{work\ done}{time} \quad P = \frac{W}{t}$$

Example: a lamp with greater power will be brighter because it transfers more energy from electrical energy to light and heat energy in a given time.

1.8 Pressure

Pressure is the force per unit area.

$$pressure = \frac{force}{area} \quad p = \frac{F}{A} \quad units = pascals$$

Example: lying down on a bed of nails compared to a single nail.

- The force applied is the weight of your body.
- The total area is either a single pinpoint or many points spread out over a larger area
  - So on a bed of nails, the pressure is lower as the area is greater.

An object in a fluid experiences pressure at right angles to all its surfaces.

- The pressure beneath a liquid's surface increases with depth and density because it is caused by the gravitational force of the fluid above that point.

The change in pressure beneath the surface of a liquid can be calculated:

$$change\ in\ pressure = pressure\ x\ gravitational\ field\ strength\ x\ height \quad \Delta p = \rho g \Delta h$$