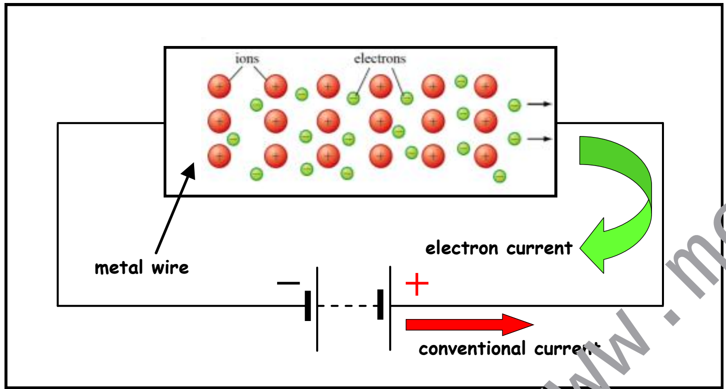
2.1.1 CHARGE & CURRENT

Electric Charge (Q)

- **Electric charge** is a property possessed by **protons** and **electrons**.
- The charges carried by the electrons and protons within atoms are **equal in size** **(= 1.6 x 10^{-19} C)** and **opposite in sign (+ve in protons and -ve in electrons)**.

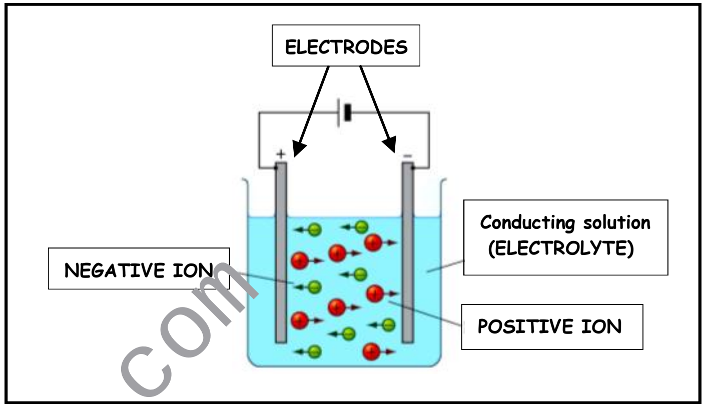
Electric Current (I)

ELECTRIC CURRENT (I) is the rate of flow of electric charge, carried by charged particles such as electrons.



- Inside the metal wire there are some negatively charged **electrons** which are free to move about. These electrons which are not tightly bound to the metal atoms are called **free** or **conduction** electrons.
  When a battery is connected to the wire as shown above, the **free** electrons experience an electric force which causes them to drift between the metal ions towards the positive terminal. It is this electron drift which constitutes the **ELECTRIC CURRENT**.

ELECTRON FLOW is in the opposite direction to CONVENTIONAL CURRENT.



- A current can also be due to **positive** and **negative** charges moving in opposite directions.
  An **ELECTROLYTE** contains both **positive** and **negative IONS** and when electrodes connected to a cell are placed in such a solution, the negative ions move towards the positive electrode and the positive ions towards the negative electrode.

- **CHARGE = CURRENT x TIME**

$$Q = It$$

(C) (A) (s)

1 COULOMB (C) is the quantity of charge which flows past a point in a circuit in a time of 1 SECOND (s) when the current is 1 AMPERE (A).

$$1\ A = 1\ C\ s^{-1}$$

Kirchhoff's First Law

At a junction in a circuit, **the sum of the currents entering the junction is equal to the sum of the currents leaving the junction.**

Kirchhoff's first law is a consequence of the principle of the **conservation of electric charge.**

Equation for Current in a Conductor – I = nAve

$$I = nAve$$

(Current/A) (number density/m^{-3}) (cross-sectional area/m^2) (drift velocity/m s^{-1}) (electron charge/C)

NOTE

- **n is different for different metals** (e.g. for copper, $n = 8 \times 10^{28}$ m^{-3} which is why it is such an excellent electrical conductor).

- **v is very small** (typically, **<1 mm s^{-1}**).

  The reason for this is that as the free electrons move along the wire, they have numerous, random collisions with the vibrating metal ions, which makes their motion very haphazard.
  So, even though the actual velocity of an electron between collisions is **≈ 10^6 m s^{-1}**, the average drift velocity **≈ 10^{-3} m s^{-1}**.

Conductors, Semiconductors and Insulators

- **CONDUCTORS (metals)**
  Have a **very high electron density (n) (≈ 10^{29} m^{-3} = 10^{20} mm^{-3}).** That is what makes them good conductors.

- **INSULATORS (rubber, plastic)**
  Have a **much lower electron density (n) (≈ 10^9 m^{-3} = 1 mm^{-3}).** This means that there is only 1 electron which is free to move per mm^3 and that is why insulators cannot conduct.

- **SEMICONDUCTORS (silicon, germanium)**
  Have an **electron density (n) (≈ 10^{19} m^{-3} = 10^{10} mm^{-3})** which lies between that of a conductor and an insulator. The value of n increases with increasing temperature, which means that it behaves as an insulator when it is cold and as a conductor when it is warm.

2.2.1 CIRCUIT SYMBOLS

Symbol	Component name	Symbol	Component name
	connecting lead		variable resistor
	cell		microphone
	battery of cells		loudspeaker
	fixed resistor		fuse
	power supply		earth
	junction of conductors		alternating signal
	crossing conductors (no connection)		capacitor
	filament lamp		thermistor
	voltmeter		light-dependent resistor (LDR)
	ammeter		semi-conductor diode
	switch		light-emitting diode (LED)

2.2.2 E.m.f. and p.d.

The **POTENTIAL DIFFERENCE (p.d.) or VOLTAGE** between two points in a circuit is the amount of **electrical energy** transferred to **other energy forms per coulomb** of charge flowing between the points.

Potential difference is measured in .... **VOLTS (V).**

1 VOLT is the potential difference between two points in a circuit in which **1 joule** of electrical energy is transferred to other energy forms when **1 coulomb** of charge flows between them.

1 VOLT = 1 JOULE PER COULOMB

$$1\ V = 1\ J\ C^{-1}$$

- If **W** (J) of **electrical energy** is transferred when **Q** (C) of **charge** flows between two points in a circuit, then the **potential difference**, **V** (V) between the two points is given by :

$$V = \frac{W}{Q}$$

(V) (J) (C)

So, $W = QV$

And since, $Q = It$,

$$W = ItV$$

(J) (A) (s) (V)

The **ELECTROMOTIVE FORCE (e.m.f.)** of an electrical source is the **electrical energy** given to each **coulomb** of charge which passes through the source. It is also measured in volts.

- The difference between **electromotive force (e.m.f.)** and **potential difference (p.d.)** may be summarised as follows :

E.m.f. (the voltage across an electrical source) is a voltage where ....

Electrical energy is being **transferred from the source to the charge.**

p.d. (the voltage across circuit components) is a Voltage where ....

Electrical energy of the charge is being **transferred to other energy forms in the circuit components.**

2.2.3 RESISTANCE

RESISTANCE ....

- Of a conductor or component is a measure of its opposition to the flow of charge (i.e. to electric current) and it is caused by the repeated collisions between the charge carriers (usually electrons) in the material with each other and with the fixed positive ions of the material. It is measured in **OHM (Ω).**

$$\text{Resistance} = \frac{\text{potential difference across component}}{\text{current through component}}$$

$$R = \frac{V}{I}$$

(Ω) (v) (A)

A conductor has a resistance of **1 ohm (Ω)** if the current in it is **1 ampere (A)** when the pd across it is **1 volt (V).**

$$1\ \Omega = 1\ V\ A^{-1}$$

Ohm's Law

OHM'S LAW states that the **pd (or voltage)** across a metallic conductor is directly proportional to the **current** through it, so long as the physical conditions (e.g. temperature) remain constant.

i.e. $V \propto I$

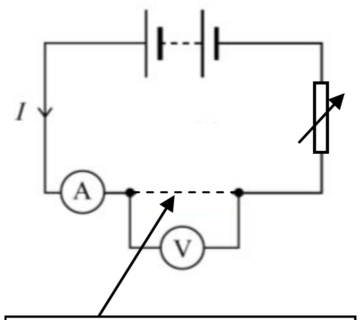
- This is equivalent to saying that the **resistance (R)** of a metallic conductor **is constant so long as the physical conditions remain the same.**
- An **ohmic conductor** is one which obeys **Ohm's law**. For such a conductor : V = I

Current-Voltage (I/V) Characteristic Graphs

- The circuit shown opposite is used to obtain a set of **corresponding I-V values** for a given component (fixed resistor, filament lamp or light-emitting diode).

These values are then used to plot a **current-voltage (I-V) graph**.

The pd (or voltage) across the component is varied by the combined use of a variable power supply and a variable resistor in series with the component.



The component under test can be :

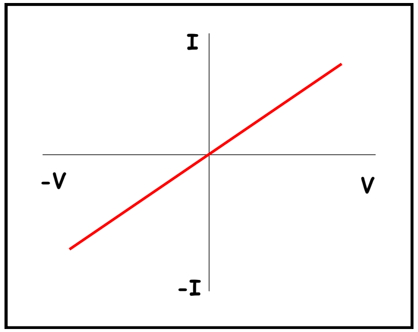
A **fixed resistor** or **wire at constant temperature.**

A **filament lamp.**

A **light-emitting diode.**

Fixed Resistor or Wire At Constant Temperature

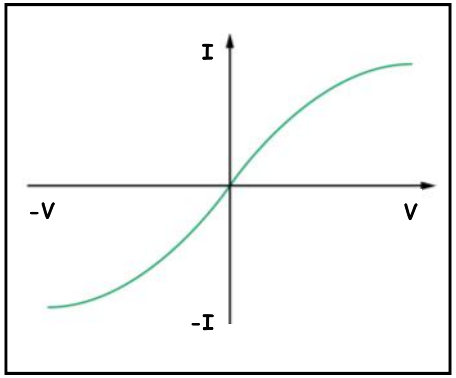
- A fixed resistor or wire at constant temperature obeys **Ohm's law** (i.e. it is an **ohmic conductor**), so its resistance remains constant.
- The pd (V) across a fixed resistor or wire is directly proportional to the current (I) through it, so the I-V graph is a **best-fit straight line through the origin.**



Gradient of the I/V graph = 1/R

Filament Lamp

- A filament lamp does **not obey Ohm's law** (i.e. it is a **non-ohmic conductor**).
- The I-V graph is **curved** with the current (I) being less than expected at the higher values of pd (V).



- The filament **resistance increases** with increasing pd (V).

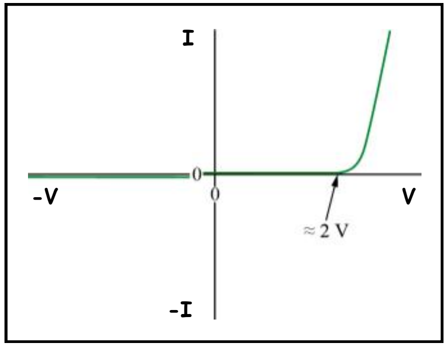
This is because as the **pd (V)** across the filament **increases**, its **temperature increases** and this makes the metal atoms vibrate with **greater amplitude**, causing a **greater opposition** to the flow of electrons (i.e. current).

Light-Emitting Diode (LED)

- This is a semi-conductor device which emits light when it is operating.

- An **LED** does **not obey Ohm' law** (i.e. it is a **non-ohmic conductor**).

- The I-V graph for a typical LED is shown opposite. The positive side of the graph is obtained with the LED **'positively biased'**.



- For pd (V) < ≈ **2V**, the current (I) is ≈ 0, so the LED has almost infinite resistance. The LED starts to conduct at its **threshold pd (≈ 2V)** and its resistance decreases dramatically for pd's > 2V.

  The negative side of the graph is obtained by reversing the connections to the supply. The LED is then said to be **'negatively-biased'**. It then has almost infinite resistance and allows only a tiny current through it.

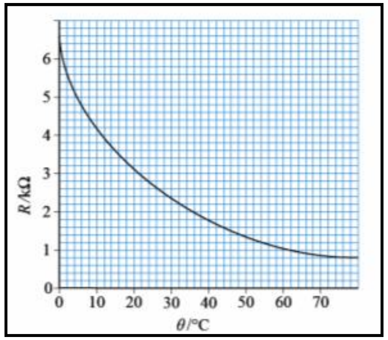
- Different LED's emit light of different wavelength (colour) and they have been traditionally used as indicator lights on appliances such as DVD players, TV sets etc.

  Some more modern versions are replacing the filament lamps used in traffic lights. Although they are more expensive to manufacture, LED's are much more energy efficient and cheaper to run than filament lamps.

Thermistors

- These are components (made from metal oxides such as manganese & nickel) whose **resistance changes very rapidly with temperature.**

In **negative-temperature coefficient** thermistors, the resistance **decreases** nearly **exponentially** with increasing temperature as shown opposite.



NTC's used in schools have :

R = many 1000's Ω at θ = 20°C

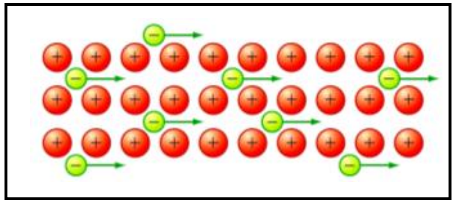
R = 50-100 Ω at θ = 100°C

Metallic Resistance Variation With Temperature

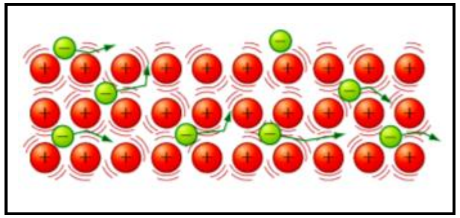
The resistance of a pure metal increases linearly with increasing temperature.

Consider a section of a metal wire to which a pd is applied.

At **LOW** temperatures, the electrons are able to drift past the positive metal ions with relative ease because they have few collisions to slow them down. This means that the **resistance is low.**



At **HIGHER** temperatures, the positive ions **vibrate with greater amplitude.** As a result, the electron-ion collisions are more frequent and this means that the flow of electrons is slowed down (i.e. the current is reduced).

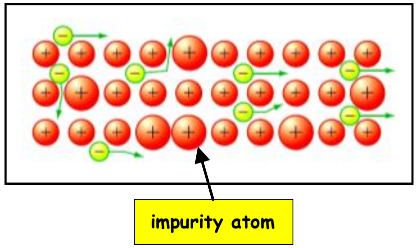


This means that the **resistance is higher than at lower temperatures.**

The resistance of an impure metal also increases linearly with increasing temperature, but it is greater than that of a pure metal.

- The fact that the impurity atoms and the metal ions are **different in size** causes an increase in the **frequency of the collisions** experienced by the drifting electrons.

  This extra opposition to the flow of electrons means that the resistance is made greater by the presence of impurity atoms in the metal.



2.2.4 RESISTIVITY

The **resistivity (ρ)** of a material is the **resistance(R)** of a sample of the material having **unit length** and **unit cross-sectional area**.

$$\text{resistance} = \frac{\text{resistivity} \times \text{Length}}{\text{cross-sectional area}}$$

$$R = \frac{\rho L}{A}$$

R (Ω), ρ (Ωm), L (m), A (m^2)

SI unit of **resistivity** is .... the **Ohm-metre (Ωm)**

How Resistivity Varies With Temperature

- **METALS** - **Resistivity increases with increasing temperature**

  This is because an increase in temperature causes increased vibration of the metal ions and this means an increase in the frequency with which the drifting electrons collide with them.

- **SEMICONDUCTORS** - **Resistivity decreases with increasing temperature**

  An increase in temperature has two effects in a semiconductor :

  - There is an increase in the electron-ion collision frequency. This means **increased resistivity**.
  - More electrons break free of their atoms, so there is an increase in the number of electrons available for conduction. This means **decreased resistivity**.

  The second effect dominates and so the **resistivity** of a semiconductor **decreases** with increasing temperature.

2.2.5 ELECTRICAL POWER

Electrical Power (P) of an appliance or device is the rate at which it transfers electrical energy into other energy forms.

The SI unit of **electrical power** is ...... the **WATT (W)**.

- Consider an amount of charge **(Q)** which flows under the influence of a pd **(V)**.

  Then, energy transferred, $W = QV$ (and since $Q = It$)

  $$W = ItV$$

  (J) (A) (s) (V)

- Also, electrical power, $P = \frac{W}{t} = \frac{ItV}{t}$

  $$P = IV$$

  (W) (A) (V)

- Also, since $V = IR$, $P = IV = I \times IR$

  $$P = I^2R$$

  (W) (A) (Ω)

- Also, since $I = V/R$, $P = IV = V/R \times V$

  $$P = \frac{V^2}{R}$$

  (W) (V) (Ω)

$P = IV$

This equation gives the rate of production of **ALL** forms of energy, So it can be used for **ANY** device

$P = I^2R$ **$P = V^2/R$**

These two equations are only **VALID** when **ALL** the electrical energy is transferred to heat energy, so it can only be used for a **PURE RESISTOR**.

Fuses

A **FUSE** is an **excessive current protection** device.

- It essentially consists of a metal wire or strip which **melts** as soon as the **current exceeds the value for which the fuse is rated.**
  This **breaks** the circuit in which the fuse is connected and so **protects** all the components in the circuit from damage due to excessive current.

- Fuses are commonly marked with the **maximum current** (called the fuse **current rating**) which they can carry before melting.

- Choose the fuse with the current rating which is **GREATER THAN** and **CLOSEST TO** the current-value calculated for the circuit or appliance.

Kilowatt-hour (kWh)

The **Kilowatt-hour (kWh)** is the amount of energy transferred to other energy forms by a device having a power rating of **1 kilowatt (kW)** when it is used for **1 hour (h)**.

The number of **kWh** or **'units'** which have been consumed and hence the **cost** of using an electrical appliance for a given time may be calculated from :

cost (p) = **power rating** (kW) × **time used** (h) × **cost per kWh**

2.3.1 SERIES AND PARALLEL CIRCUITS

Kirchhoff's Second Law

In any closed loop in a circuit, **the sum of the emf's is equal to the sum of the pd's around the loop.**

Kirchhoff's second law is a consequence of the **PRINCIPLE OF CONSERVATION OF ENERGY.**

Resistors Connected in SERIES

For any number of resistors connected **in SERIES**, the **TOTAL RESISTANCE (R_T)** is given by :

$$R_T = R_1 + R_2 + R_3 + \ldots$$

Resistors Connected in PARALLEL

For any number of resistors connected **in PARALLEL**, the **TOTAL RESISTANCE (R_T)** is given by :

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$$

For resistors connected **IN PARALLEL** :

- The **LOWEST** value resistors carry the **GREATEST** proportion of the current.
- The **TOTAL RESISTANCE** of the combination is **LESS** than the **SMALLEST** resistance in the combination.

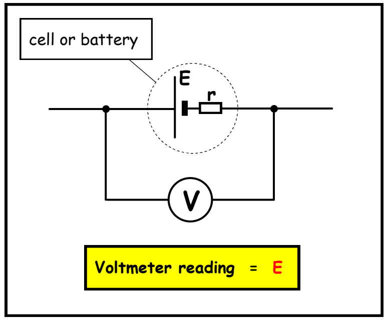
SPECIAL CASE FOR RESISTORS IN PARALLEL

- If **(N)** resistors having the same resistance **(R)** are connected **IN PARALLEL**, the **TOTAL RESISTANCE (R_T)** is given by :

$$R_T = \frac{R}{N}$$

E.m.f. (E), Terminal p.d. (V) and Internal Resistance (r)

- All sources of emf have some **INTERNAL RESISTANCE (r)** , since they are made from materials (e.g. metal wires, electrodes, chemical electrolytes) which have some electrical resistance.



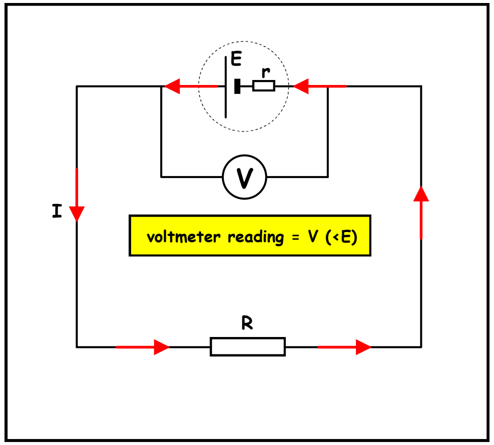
- If a voltmeter is connected across the terminals of an electrical supply (e.g. a cell or battery), it indicates what is called the **TERMINAL PD (V)** of the cell or battery.

If the cell or battery is not part of an external circuit and the voltmeter is **'ideal'** (i.e. it has **infinite resistance**), then **zero current** is drawn and :

voltmeter reading = cell emf (E)

The **emf (E)** of a cell or battery can be defined as its **terminal p.d. when it is NOT supplying a current.**

If an external circuit is connected to the cell or battery, the reading on the voltmeter drops to a value **less than E.**



This is because **when there is a current through the cell, some of its energy is converted into heat by the cell's internal resistance.**

The decrease in voltage is called the **'LOST VOLTS'** of the cell and it is proportional to the current.

The reading (V) which is < E indicated by the voltmeter is the **TERMINAL PD** of the cell and also the **pd across the resistor R.**

Applying Kirchhoff's Law 2 to the circuit

Emf of the cell = **terminal pd** (= pd across R) + **pd across the internal resistance**

$$E = V + Ir$$

$$E = IR + Ir = I(R + r)$$

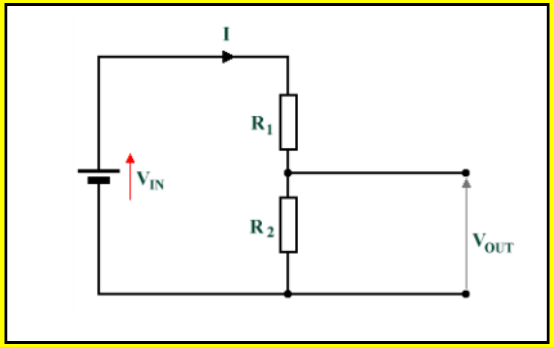
$$I = \frac{E}{(R + r)}$$

Some Effects of Internal Resistance (r)

- Low voltage sources from which large currents are drawn (e.g. car batteries) should have LOW internal resistance, otherwise their terminal PD (V = E - Ir) would be very low.
- High voltage sources (e.g. 5 kV supplies which are sometimes used in schools) have a HIGH internal resistance so as to limit the current supplied should they be short-circuited accidentally.
- The headlamps on a car will dim if the vehicle is started while they are switched on. This is because the starter motor draws a large current and this causes the battery terminal PD (V = E - Ir) to drop sharply.

2.3.2 PRACTICAL CIRCUITS

Potential Divider Circuit and Equation



The OUTPUT VOLTAGE or PD (V_o) across R_2 is given by :

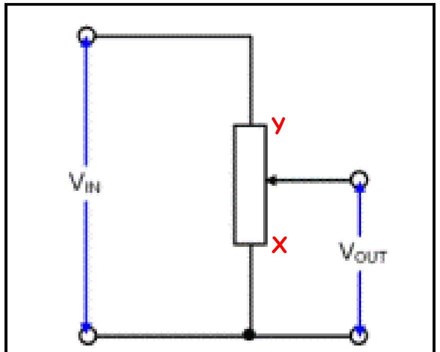
$$V_o = V_i \times \frac{R_2}{(R_1 + R_2)}$$

Supplying a Variable p.d.

The potential divider circuit shown opposite uses a variable resistor to give a continuously variable output pd from a fixed input pd.

By moving the sliding contact on the variable resistor, the value of the OUTPUT PD (V_o) can be adjusted :

- From a minimum of 0 V (sliding contact at position X).
- To the maximum value when it is equal to the INPUT PD (V_i) (sliding contact at position Y).

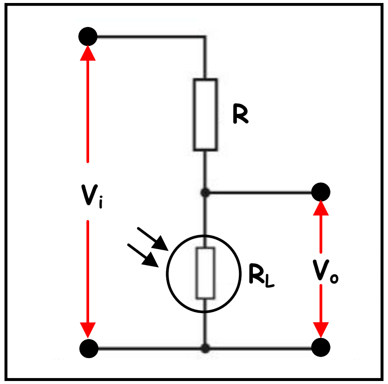


Light-Dependent Potential Divider

A light-dependent resistor (LDR) may be used in a potential divider to provide an output pd (V_o) which varies with light intensity.

The OUTPUT PD (V_o) is given by :

$$V_o = \frac{V_i R_L}{(R_L + R)}$$



In BRIGHT LIGHT

R_L is low (≈ 50 to 100 Ω) compared with R. So the output pd (V_o) is very small.

As the light intensity decreases, R_L increases.

In TOTAL DARKNESS

R_L is very high (≈ 10 MΩ) compared with R. So the output pd (V_o) has its maximum value (≈ V_i).

Since the output pd depends on light intensity, this potential divider could be used to control any process which is **light-level dependent.**

At the simplest level, this could mean **automatically switching on street lights when darkness falls.**

A switching circuit could be set to operate when V_o reaches a pre-determined value, corresponding to a particular light intensity level. If **R** were replaced by a **variable resistor**, it would allow some manual adjustment of the value of **Vo** at a particular light intensity.

If **R** and R_L were interchanged, V_o will **increase** as the **light intensity increases.** This could be used in a circuit to set off an alarm when a light is switched on.

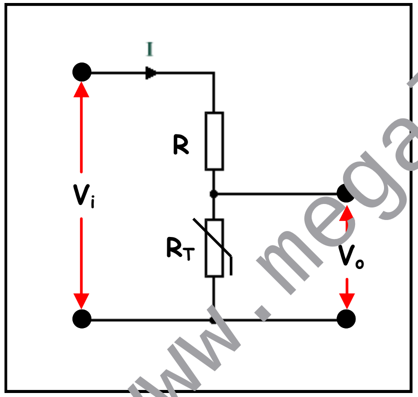
Temperature-Dependent Potential Divider

A **thermistor** is a device whose resistance varies markedly with temperature.

The resistance of a **negative temperature coefficient (NTC)** thermistor **decreases** with **increasing** temperature.

The **output p.d. (V_o)** is given by :

$$V_o = \frac{V_i R_T}{(R_T + R)}$$



When temperature is HIGH

R_T is **small** compared with **R** and so V_o will be **small.**

When temperature is LOW

R_T is **large** compared with **R** and so V_o will be **large.**

This **temperature-dependent** potential divider could form part of a circuit used to trigger a frost alarm or to switch on a heating system in order to keep the temperature above a certain value.

Replacing the fixed resistor **R** with a **variable resistor** allows manual adjustment of the 'trigger' temperature.

If R_T and **R** are interchanged, V_o will then **increase** with **increasing** temperature. Such a potential divider could form part of a circuit used to switch on an air-conditioning system when the temperature exceeds a certain value.

Advantages of Using Dataloggers

A **DATALOGGER** is an electronic device which enables data from an external sensor to be recorded over a given time period.

It can be interfaced with a computer which analyses the data and displays the information graphically.

The **advantages of a datalogger** for monitoring physical changes are :

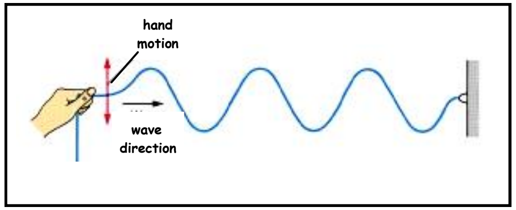
- The data is recorded automatically over any desired period.
- The collected data is continuously processed and displayed in a clear, graphical form.

2.4.1 WAVE MOTION

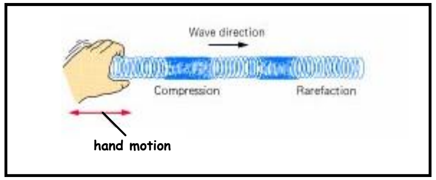
Progressive Waves

Waves which travel through a material or through a vacuum and transfer energy from one point to another.

- A series of waves (similar to **ocean waves**) can be generated in a long piece of rope which is fixed at one end and moved repeatedly at right angles to its length.



- Waves (similar to **sound waves**) are produced in a spring coil which is fixed at one end while the other end is repeatedly moved as shown.



Wave Classification

Waves can be :

MECHANICAL

Waves which need a substance for their transmission.

- Ocean waves.
- Sound waves.
- Waves along a spring coil or rope.
- Seismic waves.

ELECTROMAGNETIC

Waves which do NOT need a substance for their transmission.

Gamma-rays, X-rays, ultra-violet (UV) visible light, infra-red (IR), microwaves, radio waves

TRANSVERSE WAVES

Waves in which the particles of the medium in which a wave is moving vibrate **perpendicular** to the direction of wave travel.

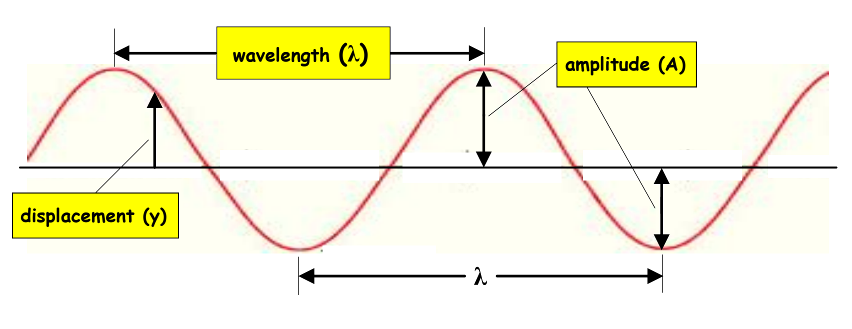
- **Ocean waves**
- **Secondary seismic waves**
- **All electromagnetic waves**

LONGITUDINAL WAVES

Waves in which the particles of the medium in which a wave is moving vibrate **parallel** to the direction of wave travel.

- **Sound waves**
- **Primary seismic waves**

Terms Associated With Waves



DISPLACEMENT (y) / metre (m)

The **distance** and **direction** of a vibrating particle in a wave from its undisturbed position.

AMPLITUDE (A) / metre (m)

The **maximum displacement** of any particle in a wave from its undisturbed position.

WAVELENGTH (λ) / metre (m)

The distance between two **consecutive points** on a wave which are **in phase** with each other (e.g. the distance between two **consecutive crests** or **troughs**).

PERIOD (T) / second (s)

The time taken for one complete wave to pass a fixed point.

OR

The time taken for one complete oscillation of a particle in the wave.

FREQUENCY (f) / hertz (Hz)

The number of complete waves passing a fixed point per second.

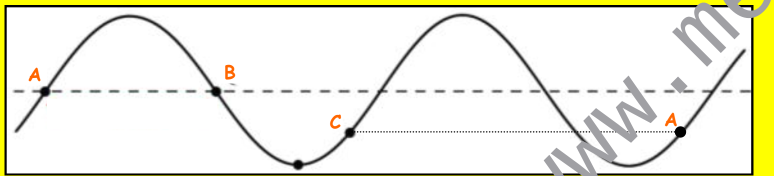
OR

The number of complete oscillations per second of a particle in the wave.

PHASE DIFFERENCE (Φ) / degrees or radians

The phase difference between two vibrating particles in a wave is **the fraction of a cycle** between the vibrations of the two particles.

Phase difference is measured in **DEGREES** or **RADIANS**.



- Particles at points **D** and **E** which are **one wavelength** apart, vibrate **in phase** with each other. The **phase difference** between the particles at these two points is **360° (=2π rads)** (which is the same as **0°**).

- Particles at points **A** and **B** which are **½ a wavelength apart**, vibrate in **antiphase**. The **phase difference** between the particles at these two points is **180°(=π rads)**.

WAVE SPEED (v or c) / metre per sec (m s^{-1})

This is the speed with which energy is transmitted by a wave.

Derivation of $v = f\lambda$

Consider a wave having **wavelength (λ)**, **period (T)**, **frequency (f)** and moving with **speed (v)**

In time (T) the wave will travel a distance (λ).

$$\text{wave speed, } v = \frac{\text{distance travelled}}{\text{time taken}} = \frac{\lambda}{T}$$

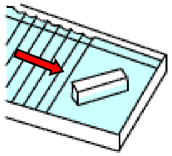
And since, $T = 1/f$, $\quad v = \dfrac{\lambda}{1/f}$

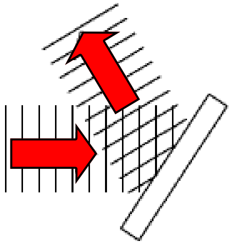
Hence :

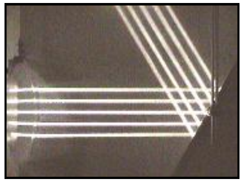
$$\boxed{v = f\,\lambda}$$

v (m s^{-1}), f (Hz), λ (m)

Reflection of Waves







The angle between the reflected wavefronts and the surface = the angle between the incident wavefronts and the surface.

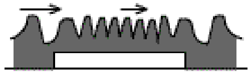
So the direction of the reflected wave is at the same angle to the reflector as the direction of the incident wave.

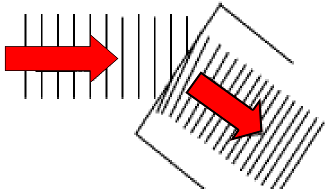
When a ray of light is directed at a plane mirror, the angle between the reflected ray and the mirror = the angle between the incident ray and the mirror.

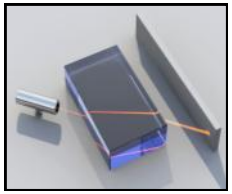
Sound waves are reflected in The same way.

Refraction of Waves

Refraction occurs when waves change their speed. Water waves slow down when they pass from deep into shallower water.







When the water waves are incident at the DEEP-SHALLOW boundary at an angle, they change direction and their wavelength (λ) decreases.

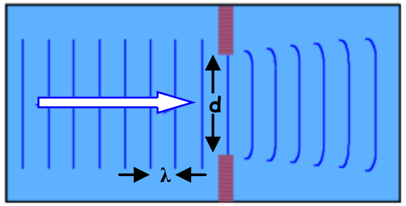
This is because $v = f\lambda$ and since v increases and f stays the same, λ must decrease.

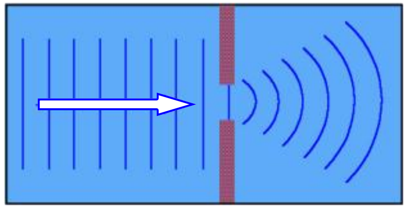
When a ray of light is directed at a parallel-sided glass block at an angle, it is also refracted.

This is because the light waves slow down and so change direction when they pass from air into glass.

Diffraction of Waves

Diffraction is the spreading of waves when they pass through a gap or around an obstacle.





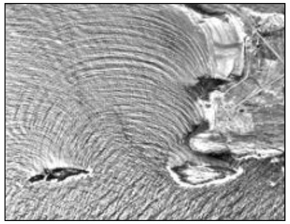
When the gap width (d) is LARGE compared to the wavelength (λ) of the incident waves, the diffraction effect is SMALL.

As the gap width (d) is decreased (with the wavelength (λ) kept the same), the diffraction effect becomes GREATER.

The diffraction effect is GREATEST when the WAVELENGTH (λ) of the waves is EQUAL to the gap WIDTH (d).

Sound waves diffract as they pass through open doorways because their wavelengths are comparable to the size of the opening. This is why a person speaking in a corridor can be overheard in an adjoining room, in spite of the fact that there is a thick wall in the way.

Sea waves are greatly diffracted as they pass through the gap between two large rocks. The effect is observable because the wavelength is of the same order of magnitude as the gap width.



Light waves diffraction is rarely observable in normal circumstances. This is because visible light wavelengths (400 - 700 nm) are tiny in comparison to the size of the gaps and objects we normally encounter.

2.4.2 ELECTROMAGNETIC WAVES

Properties Common to All Electromagnetic Waves

- **Transfer energy** from one place to another.
- Are **transverse** and can therefore be **polarised**.
- Consist of **vibrating electric and magnetic fields** which are **at right angles to each other** and **at right angles** to the **direction of travel of the wave**.
- Obey the laws of **reflection** and **refraction**.
- Obey the **wave equation $v = f\lambda$**.
- Can be **superposed** to produce **interference** and **diffraction** effects.

Typical Wavelengths of Electromagnetic Waves

WAVE TYPE	TYPICAL WAVELENGTH / m
Gamma rays	10^{-16} to 10^{-10}
X-rays	10^{-13} to 10^{-8}
Ultraviolet (UV)	10^{-8} to 4×10^{-7}
Visible light	4×10^{-7} to 7×10^{-7}
Infrared (IR)	7×10^{-7} to 10^{-3}
Microwaves	10^{-3} to 10^{-1}
Radio waves	10^{-1} to 10^{6}

Different Methods of Production of Electromagnetic Waves

WAVE TYPE	PRODUCTION METHOD
Gamma rays	Oscillating electrons in an aerial.
X-rays	Electron bombardment of a metal.
Ultraviolet (UV)	The Sun and Sunbeds.
Visible light	Natural and artificial light sources.
Infrared (IR)	Natural and artificial heat sources.
Microwaves	Electron tube oscillators.
Radio waves	Radioactive decay of nuclei.

Uses of Electromagnetic Waves

WAVE TYPE	USES
Gamma rays	Sterilisation of medical instruments / Killing cancer cells.
X-rays	To see damage to bones and teeth / Airport security scanners.
Ultraviolet (UV)	Sunbeds / Security markings that show up in UV light.
Visible light	Human sight / Optical fibres.
Infrared (IR)	Night-vision cameras / Remote controls / Optical fibres.
Microwaves	Radar / Microwave oven / TV transmissions.
Radio waves	Radio transmissions.

Describing Uses of Electromagnetic Waves

RADIO WAVES

When a radio wave interacts with a conductor, the alternating electric and magnetic fields in the radio wave exert forces on the electrons in the conductor, causing them to oscillate. This constitutes an alternating current of the same frequency as the radio wave. Using tuned circuits, particular oscillating frequencies may be selectively amplified.

MICROWAVES

The greatest application of microwaves is in communications and radar, but in recent years microwave cookers have become a regular feature of every kitchen.
A magnetron, typically operating at a frequency of 2.45 GHz delivers microwave energy to the cavity containing the food to be cooked. This microwave frequency is the same as the natural frequency of vibration of the water molecules in the food and so causes their amplitude of vibration to increase, resulting in an increase in the internal energy with a consequent rise in temperature.

INFRARED

Because of its longer wavelength, the IR emitted by living creatures can be distinguished from the background IR given out by cooler objects. Burglar alarms, night-vision equipment and thermal imaging cameras (used to locate people buried beneath the rubble of collapsed buildings) all work on the basis of IR wavelength differentiation.

Light-emitting diodes (LEDs) used in TV remote controls work by emitting an IR beam of a specific frequency.

ULTRA-VIOLET (UV)

There are three main sub-types in the UV which comes from the Sun :

UV TYPE	WAVELENGTH RANGE
UVA (Long wave)	320 nm to 400 nm
UVB (medium wave)	280 nm to 320 nm
UVC	100 nm to 280 nm

Most of the solar UV incident on Earth is absorbed as it passes through the atmosphere and about 98% of that which reaches ground level is **UVA**. The remaining 2% is mainly **UVB** since most of the **UVC** is absorbed by the ozone layer.

UVA, B and C cause damage to collagen fibres in the skin which results in premature wrinkling and ageing of the skin.

UVB induces the production of vitamin D in the skin, but it can cause sunburn and it can damage DNA in skin cells which may lead to skin cancer. High intensities of UVB can also lead to the formation of cataracts in the eyes.

SUNSCREENS filter out or absorb UVB
And so protect against sunburn and the
Possibility of skin cancer.

X-RAYS

X-rays find their greatest use in **medical imaging**, especially for the detection of broken bones.
They are also used in **chest x-rays** to identify lung diseases such as lung cancer.

Airport security scanners use x-rays to inspect the interior of luggage prior to loading onto the aircraft.

GAMMA (γ)-RAYS

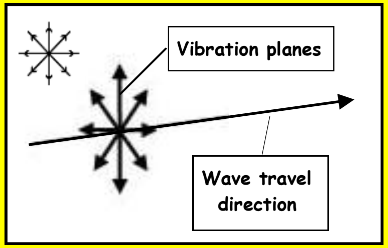
γ-rays are used to **sterilise medical equipment** (hypodermic syringes, scalpels etc.) and **to remove decay-causing bacteria** from many foods.

γ-rays are also used in the **treatment of some types of cancer.**

In **gamma-knife surgery** , multiple, concentrated beams of **γ-rays** are directed at a tumour in order to kill the cancerous cells.

Polarisation

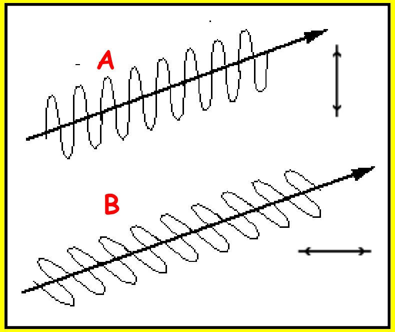
An **UNPOLARISED** wave is one which has vibrations in all directions at right angles to the direction of travel of the wave.



A **PLANE-POLARISED** wave is one in which the vibrations are in one plane only.

A is **VERTICALLY** polarised

B is **HORIZONTALLY** polarised.



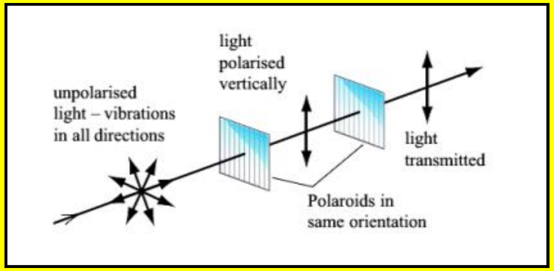
The phenomenon of polarisation distinguishes **TRANSVERSE** waves from **LONGITUDINAL** waves in that :

TRANVERSE WAVES CAN BE POLARISED, BUT LONGITUDINAL WAVES CANNOT BE POLARISED.

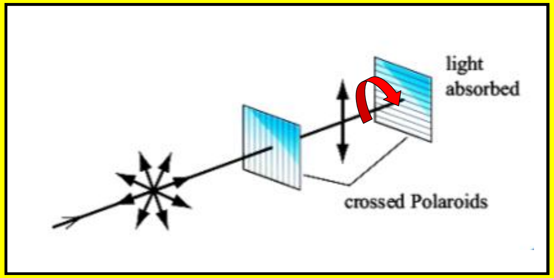
This is because the vibrations in a longitudinal wave are along the direction of motion of the wave.

Polarisation of Light

Unpolarised light becomes polarised after it passes through a piece of **polaroid**. If A second **polaroid** with its axis of polarisation the same as the first is placed in the path of the polarised light, the light is **transmitted**.



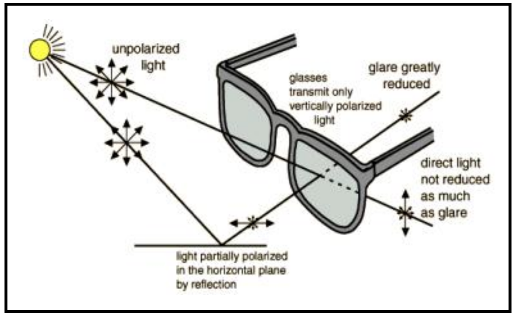
As the second **polaroid** is slowly rotated so that its polarisation axis moves from **vertical** to **horizontal**, less and less light is transmitted. Eventually, when the two polaroids have their axes at **right angles** **no light is transmitted**.



Partial Polarisation of Reflected Light

When light is reflected from any shiny surface it is **partially polarised** in the horizontal plane and produces glare.

This is easily remedied by wearing sunglasses. The polaroid in the glasses is arranged so that it will only transmit **vertically polarised** light and this greatly reduces glare which is light which has been **partially polarised in the horizontal plane**.



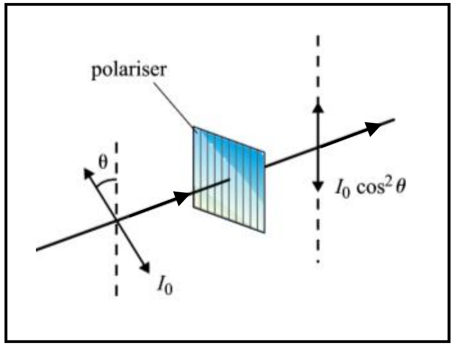
Malus's Polarisation Law

When a perfect polariser is placed in the path of a polarised light beam, the **intensity (I)** of the transmitted light is given by :

$$I = I_0 \cos^2\theta$$

I_0: initial intensity

θ: angle between the initial polarisation direction and the polariser's axis of polarisation

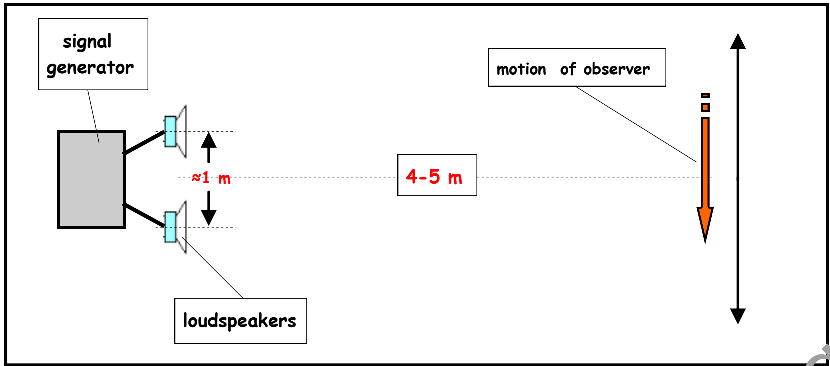


2.4.3 INTERFERENCE

Superposition of Waves

The **principle of superposition** of waves states that when two or more waves meet at a point, the **resultant displacement is the sum of the displacements of the individual waves.**

Describing Two-Source Interference Experiments



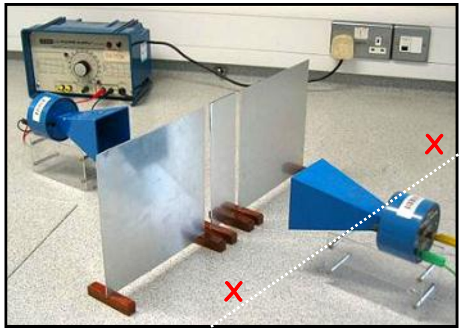
SOUND WAVES

- Two loudspeakers are connected to a single signal generator as shown in the diagram. The sound waves emitted by each speaker are then of equal frequency, wavelength and amplitude.

- An interference effect due to the superposition of the sound waves is observed in the region in front of the speakers. Alternate loud and quiet sounds are heard by an observer moving at right angles to the sound direction.

Microwaves

A **microwave transmitter** is directed towards the double gap in a metal barrier.

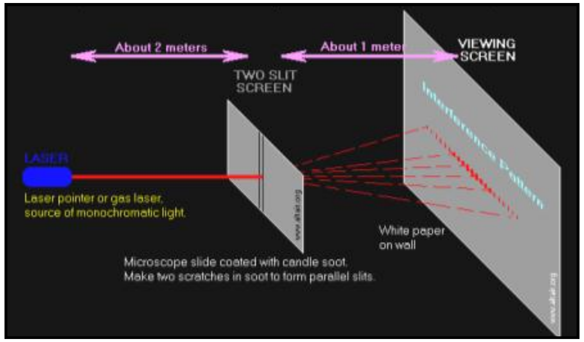


The waves diffract through the two gaps into the region beyond the barrier, where they **superpose and produce interference effects.**

A **microwave receiver** connected to a **microammeter** is moved along a line **XX**, parallel to the metal barrier. As the receiver is moved, the meter registers **HIGH** readings as it passes through regions where **CONSTRUCTIVE** interference is occurring and **LOW** readings where **DESTRUCTIVE** interference is occurring.

Light Waves

When a beam of laser light is directed onto a double slit (two clear slits on a black slide), an interference pattern of equally spaced light dots is seen on a screen placed ~1 m from the slits.

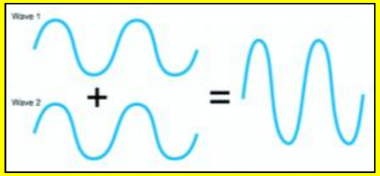


The light dots are called **INTERFERENCE FRINGES.**
They are points where light waves are arriving **in phase** with each other to give **CONSTRUCTIVE** interference. The **dark regions** in between the dots are the result of **DESTRUCTIVE** interference caused by light waves arriving in **antiphase.**

CONSTRUCTIVE AND DESTRUCTIVE INTERFERENCE

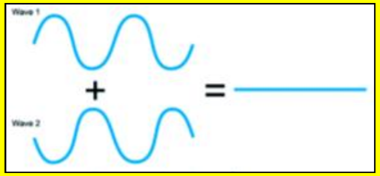
CONSTRUCTIVE

At points where waves arrive **IN PHASE** with each other, the waves reinforce each other to give a resultant wave of **larger amplitude**.



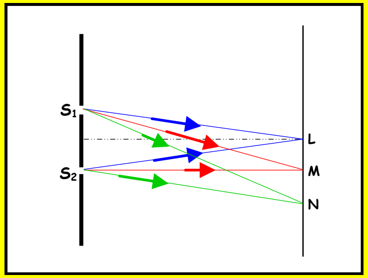
DESTRUCTIVE

At points where waves arrive in **ANTIPHASE** with each other, the waves cancel each other to give a resultant wave of **zero amplitude**.



Explaining The Interference Fringes

L is equidistant from S_1 and S_2, so the **path difference** between light waves from S_1 and S_2 = **0**. Since the waves are **in phase** when they leave S_1 and S_2, they arrive **in phase** at **L**. So **constructive** interference occurs and a **bright** fringe is formed at **L**.



The light waves arriving at **M** are in **antiphase** because the **PD** between the waves is exactly = $\frac{1}{2}\lambda$, so **destructive** interference occurs and a **dark** fringe is formed.

The light waves arriving at **N** are **in phase** because the **PD** between them is exactly = 1λ, so **constructive** interference occurs. Point **N** is the mid-point of the **second bright fringe**.

SUMMARY

path difference = $n\lambda$ → Waves arrive **in phase** → Constructive interference **bright fringe**

path difference = $(n + \frac{1}{2})\lambda$ → Waves arrive **in antiphase** → **Destructive** interference **dark fringe**

Where n = 0,1,2,3, etc..

Meaning of Terms in The Double-Slit Interference Equation

$$\lambda = \frac{ax}{D}$$

Slits separation (m) — a

fringe separation (m) — x

wavelength (m) — λ

slits-screen distance (m) — D

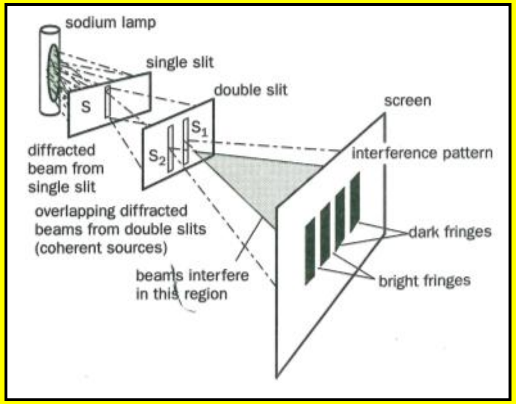
Coherent Wave Sources

Two wave sources are said to be **coherent** if the waves emitted from them are either **in phase** or have a **constant phase difference**. This implies that the sources have the **same frequency**.

Conditions For Observable Interference

- The wave sources must be **coherent**.
- The interfering waves should be of about the **same amplitude**, to give good contrast between the bright and dark fringes.

Young's Double-Slits Experiment



The sodium lamp acts as a monochromatic (single wavelength) light source and it illuminates the narrow slit **(S)**. Diffraction at **S** causes a diverging beam of light to fall on the two narrow slits **S_1** and **S_2** which are very close together and parallel to **S**. Since they are derived from a single source **S**, the two slits act as **coherent** light sources. The diffracted light beams emerging from **S_1** and **S_2** overlap in the region beyond the slits and superposition of the light waves produces an **interference pattern of bright and dark fringes** which can be seen on a white screen placed 1-2 m from the double slits.

Evidence in Favour of The Wave Theory

Young's double-slit experiment was a classical confirmation of the **wave theory of light** because the interference pattern could only be explained in terms of the superposition of light waves from the two slits.

The **bright** fringes were explained by stating that at such points the light waves arrive **in phase** and so reinforce each other (i.e. **constructive interference** occurs).

At points where the light waves arrive in **antiphase**, cancellation occurs (i.e. **destructive interference** occurs) and so a **dark** fringe is formed.

Intensity (I)

The **Intensity (I)** of a wave motion at a point is the rate at which energy is transmitted (i.e. the power) per unit area perpendicular to the wave direction.

$$\text{intensity} = \frac{\text{power}}{\text{cross-sectional area}}$$

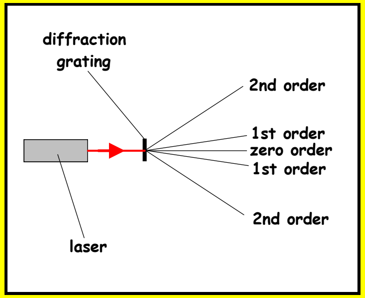
$$I = \frac{P}{A}$$

(W m^{-2}) (W) (m^2)

Intensity is proportional to amplitude^2, so **doubling the amplitude** will **quadruple the intensity**. **Trebling the amplitude** will make the **intensity 9 times as big**.

The Diffraction grating

When a beam of monochromatic light is directed at a diffraction grating, it passes through the clear spaces between the lines and it is transmitted in certain, clearly defined directions only.



The diffraction images observed include the **zero order** image which is along the straight-through position, with further images on either side which are referred to as the **1st order**, **2nd order** and so on.

Diffraction grating Equation

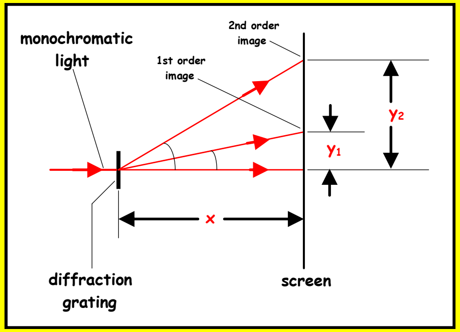
$$d \sin\theta = n\lambda$$

- diffraction angle: θ
- light wavelength: λ
- grating spacing $d = 1/N$ (N = number of lines per m.)
- diffraction order: $n = 0,1,2,3$ ....etc

Light Wavelength Measurement Using a Diffraction Grating

A beam of monochromatic light of **wavelength (λ)** is directed perpendicularly at a diffraction grating whose **grating spacing (d)** is known.

The **zero, 1st** and **2nd** order diffraction images are obtained on a screen placed at a distance **(x)** from the grating.



Diffraction angles **(θ)** for the 1st and 2nd order images are then given by :

$$\theta_1 = \tan^{-1}(y_1/x) \quad \text{and} \quad \theta_2 = \tan^{-1}(y_2/x)$$

Then, since $d \sin\theta = n\lambda$, $\lambda = d \sin\theta/n$

For the **1st order** image : $\lambda_1 = d \sin\theta_1/1$

For the **2nd order** image : $\lambda_2 = d \sin\theta_2/2$

From which an average value for the light **wavelength (λ)** is determined.

Advantages of Using Multiple Slits

The interference fringes obtained with the double-slit apparatus are **faint** and **blurred**.
This makes it difficult to measure the fringe width accurately.

Using a diffraction grating with **many slits** overcomes these problems because :

- The maxima are **much brighter** (the larger number of slits allows much more light to be transmitted).
- The maxima are **very sharp** (since constructive interference only happens in certain precise directions).

2.4.4 STATIONARY WAVES

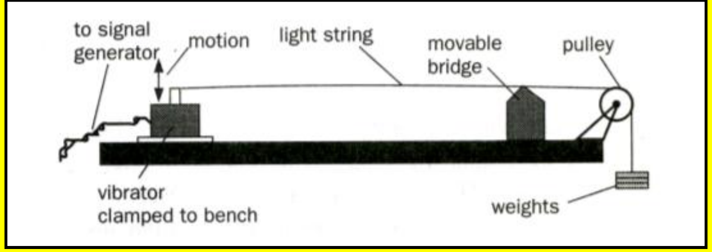
Stationary (or Standing) Waves

- Are formed as a result of superposition between two **identical** waves (i.e. same **speed, Frequency**, and approximately equal **amplitude**) **travelling in opposite directions.**
- **They do not transmit energy** from one point to another.
- They stand in a fixed position and have :

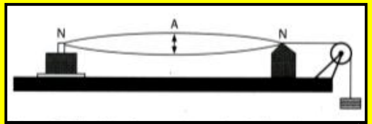
  Points of **zero displacement** called **nodes.**
  Points of **maximum displacement** called **antinodes.**

Stationary Wave Demonstrations

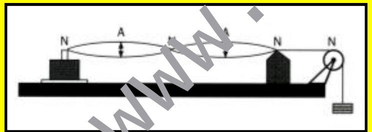
Stationary Waves in Strings



The vibrator sends out **transverse** waves along the string which are reflected from the moveable bridge. These reflected waves meet and **superpose** with waves coming from the vibrator.



As the vibrator frequency is gradually increased from a low value, a particular frequency is reached at with the string is seen to vibrate with a large amplitude stationary wave.
This is the lowest frequency at which a stationary wave is formed and it is called the **fundamental frequency (f_0)**.



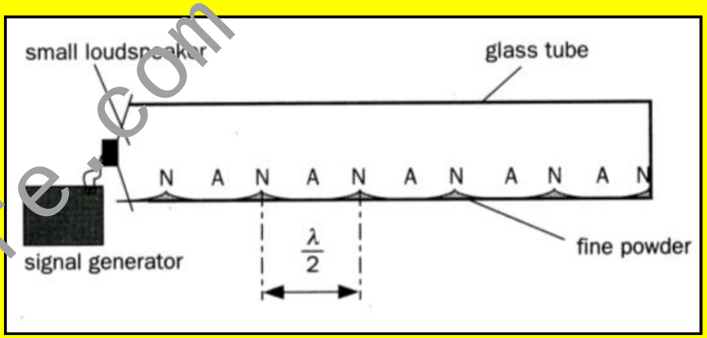
If the vibrator frequency is increased further, the single-loop stationary wave disappears and a new stationary wave having two loops is seen when the **frequency = 2 f_0**.

Further stationary waves having **3, 4, 5….** vibrating loops are seen when the vibrator frequency is increased to **$3f_0$, $4f_0$, $5f_0$…..etc.**

The frequencies at which these stationary waves occur are the **resonant frequencies** of the string under these conditions.

Stationary Waves in Air Columns

When the air at one end of a tube is caused to vibrate, a **progressive, longitudinal** wave travels down the tube and is reflected at the opposite End. The incident and reflected waves have the same **speed, frequency** and **amplitude** and superpose to form a **stationary, longitudinal** wave.

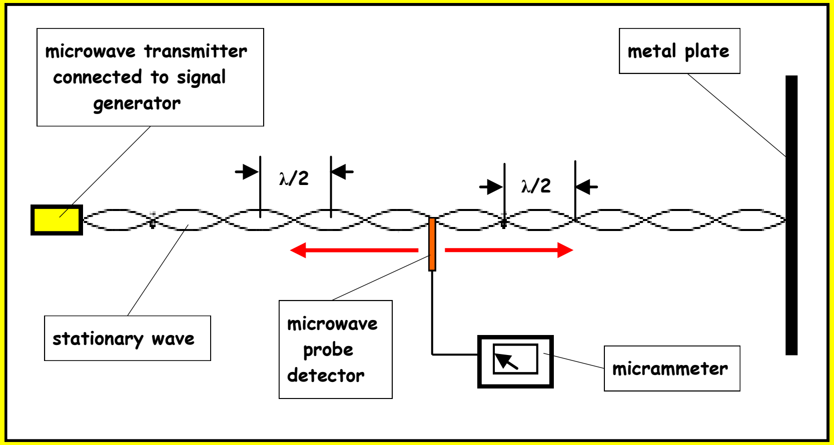


When the frequency of The sound from the loudspeaker is increased from a low value, the sound produced becomes louder at certain frequencies. These loudness peaks are caused when the air column in the tube is set into resonant vibration by the vibrating loudspeaker cone.

At these **resonant frequencies**, the fine powder in the tube forms into equally-spaced heaps. This is because the air molecules vibrate longitudinally along the tube axis and the amplitude of vibration varies from a **maximum** at the **antinodes (A)** to **zero** at the **nodes (N)**.

At the **antinode** positions the large amplitude vibration shifts the fine powder and so causes it to accumulate near the **node** positions, where the amplitude of vibration of the molecules is zero.

Stationary Waves With Microwaves



A microwave transmitter connected to a signal generator is used to direct **microwaves** at a metal plate. The microwaves are reflected from the plate and superposition between the incident and reflected waves can produce a **stationary wave.**

A microwave probe detector moved between the transmitter and the plate indicates alternating points of **maximum (antinodes, A)** and **minimum (nodes, N)** microwave intensity (i.e. high and low readings are obtained on the microammeter).

The microwave **wavelength (λ)** can be determined by measuring the distance moved by the probe detector as it goes through a number of nodes . Moving the detector a distance, **D** through say, **10** nodes, means that :

$5\lambda = D$ and so $\lambda = D/5$.

The microwave **frequency (f)** is given by the signal generator and so the **speed (c)** of the microwaves can be calculated from $c = f\lambda$.

If a loudspeaker is connected to the signal generator, a **sound** stationary wave pattern can be produced. A microphone connected to an oscilloscope is then used to detect the positions of the nodes and antinodes.

POINTS TO NOTE ABOUT ......

1. Stationary Waves in Strings

- There are points, called **NODES (N)** where the displacement of the string is **always zero**.

  There are points, called **ANTINODES (A)** where the displacement of the string is **always a maximum.**

- In the region between successive nodes, all particles are moving **in phase** with **differing amplitudes.**

  The oscillations in one loop are in **antiphase** (i.e. **180°** or **π rads** or **λ/2** out of phase) with the oscillations in adjacent loops.

Distance between adjacent nodes (or antinodes) = $\frac{1}{2}\lambda$

2. Stationary Waves in Air Columns

- The stationary wave in the air column is **longitunInal**.

- The amplitude of vibration of the air molecules is always a **maximum** at the **open end** of the tube (i.e. it is an **antinode**).

  The amplitude of vibration of the air molecules is always **zero** at the **closed end** of the tube (i.e. it is a **node**).

- All molecules between two adjacent nodes vibrate **in phase**.

  All molecules on either side of a node vibrate **in antiphase**

Distance between adjacent nodes (or antinodes) = $\frac{1}{2}\lambda$

Modes of Vibration of Stretched Strings

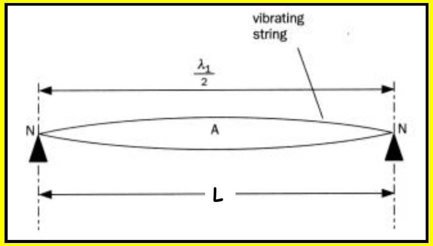
Fundamental Mode (1st harmonic)

This is the simplest and lowest possible frequency of vibration.

$L = \lambda_1/2$,   so $\lambda_1 = 2L$

$f_0 = v/\lambda_1 = v/2L$

$\boxed{f_0 = v/2L}$

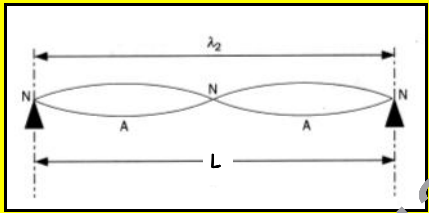


2nd Harmonic

This is the next possible frequency of vibration. In this case :

$L = \lambda_2$,   so $f_1 = v/\lambda_2 = v/L$

$\boxed{f_1 = v/L = 2f_0}$



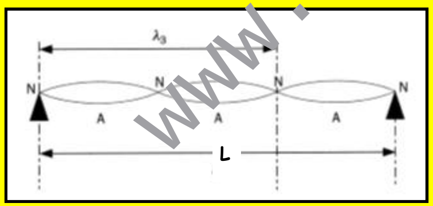
3rd Harmonic

In this case : $L = 1.5\ \lambda_3$

So $\lambda_3 = 2/3\ L$

And $f_2 = \dfrac{v}{2/3\ L} = \dfrac{3v}{2L}$

$\boxed{f_2 = \dfrac{3v}{2L} = 3f_0}$



Thus the possible vibration frequencies for a stretched string are :

f_0, $2f_0$, $3f_0$, $4f_0$, etc ..

Modes of Vibration For Closed Pipes

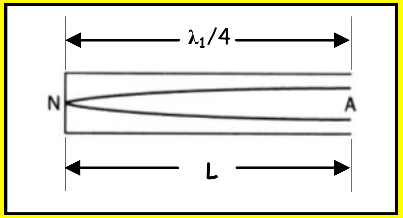
Fundamental Mode (1st harmonic)

This is the simplest and lowest possible frequency of vibration.

$L = \lambda_1/4$,   so $\lambda_1 = 4L$

$f_0 = v/\lambda_1 = v/4L$

$\boxed{f_0 = v/4L}$



NOTE that the air molecules vibrate longitudinally along the axis of the pipe, but the diagram shows these vibrations plotted along the vertical axis.

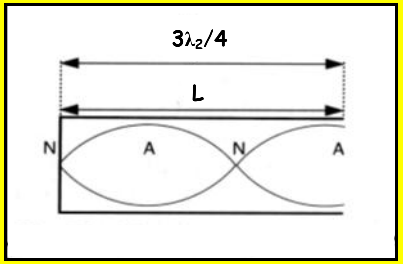
3rd Harmonic

This is the next possible frequency of vibration. In this case :

$L = 3\lambda_2/4$,   so $\lambda_2 = 4L/3$

And $f_1 = \dfrac{v}{4L/3} = \dfrac{3v}{4L}$

$\boxed{f_1 = 3v/4L = 3f_0}$



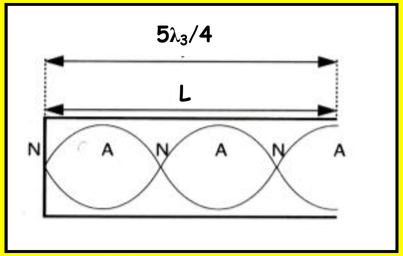
5th Harmonic

In this case : $L = 5\ \lambda_3/4$

So $\lambda_3 = 4/5\ L$

And $f_2 = \dfrac{v}{4/5\ L} = \dfrac{5v}{4L}$

$\boxed{f_2 = 5v/4L = 5f_0}$



Thus the possible vibration frequencies for a closed pipe are :

f_0, $3f_0$, $5f_0$, $7f_0$, etc ..

Modes of Vibration For Open Pipes

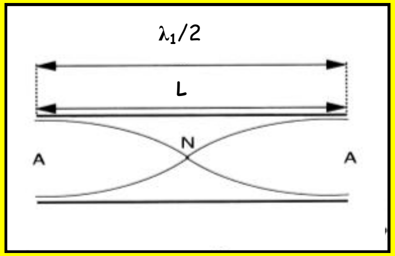
Fundamental Mode (1st harmonic)

This is the simplest and **lowest possible frequency** of vibration.

$L = \lambda_1/2$, so $\lambda_1 = 2L$

$f_0 = v/\lambda_1 = v/2L$

$\boxed{f_0 = v/2L}$



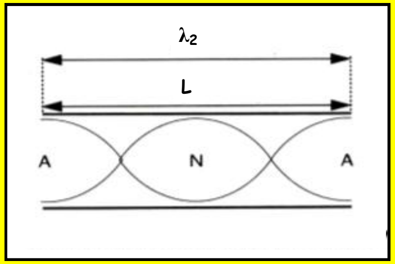
2nd Harmonic

This is the next possible frequency of vibration. In this case :

$\lambda_2 = L$

And $f_1 = \dfrac{v}{\lambda_2} = \dfrac{v}{L}$

$\boxed{f_1 = v/L = 2f_0}$



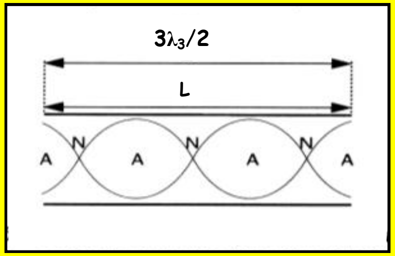
3rd Harmonic

In this case : $L = 3\lambda_3/2$

So $\lambda_3 = 2/3\ L$

And $f_2 = \dfrac{v}{2/3\ L} = \dfrac{3v}{2L}$

$\boxed{f_1 = 3v/2L = 3f_0}$



Thus the possible vibration frequencies for an open pipe are :

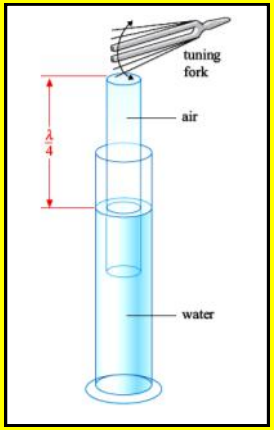
$f_0,\ 2f_0,\ 3f_0,\ 4f_0,$ etc ..

Determination of The Speed of Sound in Air

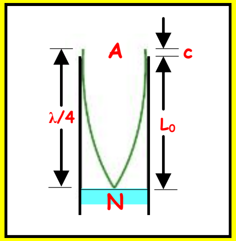
In the **resonance tube** shown opposite, the air column is set into vibration by holding a sounding tuning fork over the open end.

A given length of air column has a **natural frequency** of vibration and if the tuning fork frequency matches this, the air column is set into **resonant** vibration and the tuning fork sounds **much louder**.

With the tuning fork sounding over the open end, the inner tube is slowly raised, increasing the air column length until a **loud** sound is heard.



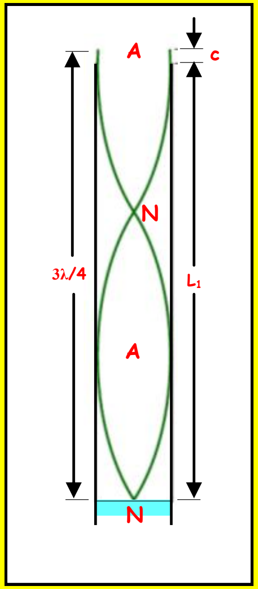
In this first resonance position the air column is vibrating in its **fundamental mode** with a **node (N)** at the closed end and an **antinode (A)** at a distance **(c)** above the open end. Then :



$\boxed{\lambda/4 = L_0 + c \quad ......(1)}$

By further increasing the length of the air column, a **second resonance position** is obtained.

The air column is now vibrating in its **first harmonic** with two **nodes (N)** and two **antinodes (A)**. In this case :



$\boxed{3\lambda/4 = L_1 + c \quad ......(2)}$

(2) - (1) : $\lambda/2 = L_1 - L_0$

So : $\lambda = 2(L_1 - L_0)$

Then, speed of sound, $v = f\lambda$,

From which : $\boxed{v = 2f(L_1 - L_0)}$

2.5.1 ENERGY OF A PHOTON

What is a Photon?

A **photon** is a **quantum** (a brief burst) of energy of electromagnetic radiation.

- When an atom **emits** a photon, its energy **decreases** by an amount equal to **the energy of the emitted photon.**
- When an atom **absorbs** a photon, its energy **increases** by an amount equal to **the energy of the absorbed photon.**
- The **energy (E)** of a photon is directly proportional to the **frequency (f)** of the radiation and it is given by the equation :

$$\boxed{E = hf}$$

E (J), f (Hz), h (Planck's constant = 6.63×10^{-34} J s)

Since $c = f\lambda$:

$$\boxed{E = \frac{hc}{\lambda}}$$

c (speed of e.m. radiation in a vacuum = 3.0×10^{8} m s^{-1}), λ (Photon wavelength in m)

The Electronvolt (eV)

1 electronvolt (eV) is the energy gained by an electron when it moves through a potential difference of **1 volt**.

If an electron (charge, $Q = e = 1.6 \times 10^{-19}$ C) moves through a pd of 1V, the **kinetic energy (E)** gained is given by :

$$E = QV = (1.6 \times 10^{-19}) \times (1) = 1.6 \times 10^{-19} \text{ J}$$

$$\boxed{1\text{eV} = 1.6 \times 10^{-19} \text{ J}}$$

To convert **eV to J**	➡	**multiply by** 1.6×10^{-19}
To convert **J to eV**	➡	**divide by** 1.6×10^{-19}

Energy Transfer Equation

Consider an electron of **charge (e)** and **mass (m)** which is initially **at rest** and is then accelerated through a **pd (V)** to reach a **final speed (v)**. Then :

Kinetic energy gained by the electron = Work done on the electron by the accelerating pd

$$\boxed{\tfrac{1}{2} mv^2 = eV}$$

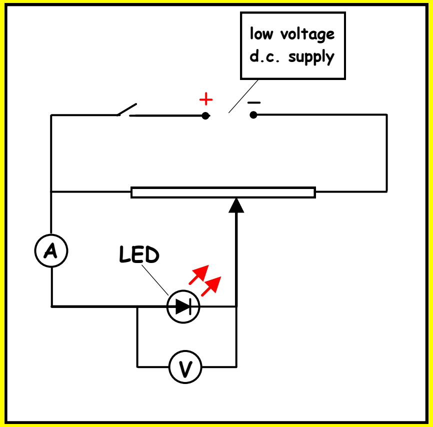
m (kg), v (m s^{-1}), e (C), V (V)

Rearranging the above gives us an equation for the **electron speed (v)** :

$$\boxed{v = \sqrt{(2eV/m)}}$$

Experimental Estimation of The Planck Constant (h)

The **threshold voltage (V)** of each of several LEDs of different colour is determined using the circuit shown opposite.



In each case the voltmeter reading **(V)** is noted when The ammeter reading shows that the LED has just started to conduct.

The **wavelength** of the light emitted by each LED is obtained from the manufacturer's quoted value.

Analysis of Results

$$eV = \frac{hc}{\lambda}$$

So, $\quad V = (hc/e) \times 1/\lambda$

Comparing with : $\quad y = mx \quad$ (the equation of a straight line)

It can be seen that a graph of **V against 1/λ** will give a straight line graph whose **gradient (m) = hc/e.**

From which :

$$\boxed{\text{Planck's constant, } h = \text{gradient} \times e/c}$$

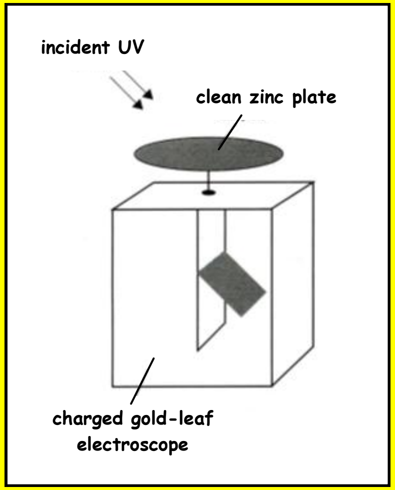
2.5.2 THE PHOTOELECTRIC EFFECT

The Photoelectric Effect

Photoelectric Emission is the ejection of electrons from the surface of a metal when it is exposed to electromagnetic radiation of **sufficiently high frequency (or short wavelength).**

Demonstration of The Photoelectric Effect

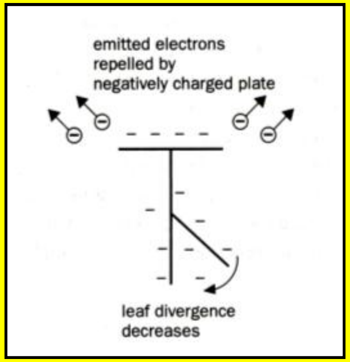
When a gold-leaf electroscope is given a charge, the thin gold leaf acquires the same charge as the stem, is repelled and rises.



A freshly cleaned zinc plate is placed on the electroscope cap. If the electroscope is then given a **negative charge**, the leaf rises and stays up. **Ultra-violet** radiation from a mercury vapour lamp is then directed at the zinc plate and the leaf is seen to fall slowly, showing that the electroscope is **discharging**.
A glass sheet (which absorbs UV) placed between the lamp and the zinc halts the leaf's descent, showing that it is the UV which is causing the discharge

EXPLANATION

The photoelectrons which are emitted from the zinc plate will be repelled by the negative charge on the electroscope



The continuous loss of electrons, which is the result of photoelectric emission from the zinc surface, is responsible for the discharge of the electroscope.

POINTS TO NOTE ABOUT THE PHOTOELECTRIC EFFECT

1. **Increasing** the **intensity** (i.e. **brightness**) of the radiation incident on a metal surface **increases** the **number of photons arriving per second** and so **increases the number of electrons emitted per second.**

2. If the incident radiation **frequency (f)** is less than a certain **threshold frequency (f_0),** no photoelectric emission will occur, no matter how intense the radiation is.

Similarly, if the incident radiation **wavelength (λ)** is greater than a certain **threshold wavelength (λ_0),** no photoelectric emission will occur.

3. The photoelectrons are emitted from a given metal with a range of kinetic energies, from zero up to a maximum value.

The **maximum kinetic energy (KE_{max})** of the emitted electrons **increases** as the **frequency** of the incident radiation **increases** and it is independent of the **intensity** of the radiation.

4. The **threshold frequency (f_0)** for a metal is the **minimum frequency** of electromagnetic radiation which will cause photoelectric emission.

4. The **threshold wavelength (λ_0),** for a metal is the **maximum wavelength** of electromagnetic radiation which will cause photoelectric emission.

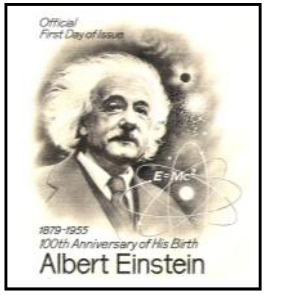
IMPLICATIONS OF THE PHOTOELECTRIC EFFECT

Although the **wave theory** could explain phenomena such as **interference** and **diffraction**, it failed to explain the **photoelectric effect**.

According to **wave theory**, photoelectric emission should happen for **all frequencies** of incident radiation. Furthermore, the **kinetic energy** of the emitted electrons should **increase with radiation intensity**.

The experimentally proven reality is that photoelectric emission does **not occur** with incident radiation **frequencies less than the threshold frequency** and the **kinetic energy** of the photoelectrons is **independent of radiation intensity**.

Albert Einstein explained the photoelectric effect in terms of the **particle nature** of electromagnetic radiation (i.e. in terms of **photons**).



Thus electromagnetic radiation may be thought of as having a **dual nature**.
Some phenomena (interference, diffraction and polarisation) are explicable in terms of its **wave nature**, but others, such as the photoelectric effect, can only be explained in terms of its **particle nature**.

Einstein's Photoelectric Effect Equation

(J s) (Hz) (J) (J)

$$hf = \Phi + KE_{max}$$

energy delivered by a photon of frequency (f)

minimum energy needed to free electrons from metal surface

maximum kinetic energy of emitted electron

KEY POINTS TO NOTE

The **work function energy (Φ)** is the minimum energy needed by an electron in order to escape from a metal surface.

The photoelectric equation shows that KE_{max} of a photoelectron depends only on the **frequency (f)** of the incident photon.

Increased intensity simply means that the incident radiation carries **more photons per second** and will so produce **more photoelectrons per second**, but it has **no effect** on the **maximum kinetic energy (KE_{max})**.

The photoelectric equation can be expressed in terms of the **wavelength (λ)** of the incident photons :

(J s) (m s^{-1})

$$\frac{hc}{\lambda} = \Phi + KE_{max}$$

(m) (J) (J)

$$KE_{max} = \tfrac{1}{2} m v_{max}^2$$

(maximum velocity of the photoelectron)

Photoelectric emission just occurs when :

incident photon energy, hf_0 = work function, Φ

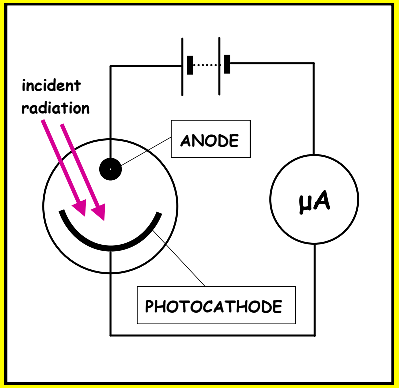
(J)

$$f_0 = \frac{\Phi}{h}$$

(Hz) (J s)

Photocell Circuit

When radiation of **frequency (f) greater than the threshold frequency (f_0)** for the metal is incident on the photocathode, electrons emitted from it are transferred to the anode.



The **photoelectric current (I)**, measured by the microammeter is proportional to the **number of electrons per second** which move from cathode to anode.

For a **photoelectric current (I)**, the **number of photoelectrons per second (N)** emitted by the cathode is given by :

$$N = I/e \quad \text{(where } e = \text{electronic charge)}$$

The PHOTOELECTRIC CURRENT is proportional to the INTENSITY of the radiation incident on the photocathode.

This is because the INTENSITY is proportional to the NUMBER OF PHOTONS PER SECOND striking the cathode.

In order to be ejected, each photoelectron absorbs a photon, so the NUMBER OF PHOTOELECTRONS EMITTED PER SECOND (i.e. the PHOTOELECTRIC CURRENT) is proportional to the INTENSITY of the incident radiation.

The MAXIMUM KINETIC ENERGY of the photoelectrons is independent of the INTENSITY of the incident radiation.

The energy gained by each photoelectron is due to the absorption of a single photon, so the MAXIMUM KINETIC ENERGY (KE_{max}) is given by :

$$\boxed{KE_{max} = hf - \Phi}$$

So, for a given metal, the MAXIMUM KINETIC ENERGY (KE_{max}) depends only on the incident photon energy (hf).

2.5.3 WAVE-PARTICLE DUALITY

The phenomena of **reflection, refraction, interference and diffraction** can all be explained using the idea of light as a **wave motion**.

The **photoelectric effect** however, requires an explanation which considers light and all other electromagnetic radiation as a **particle motion** (i.e. consisting of discrete packets of energy called **photons**).

The two, sharply contrasting ideas (**wave** and **particle**) are just different models which we use to explain the behaviour of electromagnetic radiation in different circumstances. Electromagnetic radiation can be thought of as a either a **wave** or a **particle** depending on which phenomenon we want to explain.

De Broglie's Equation

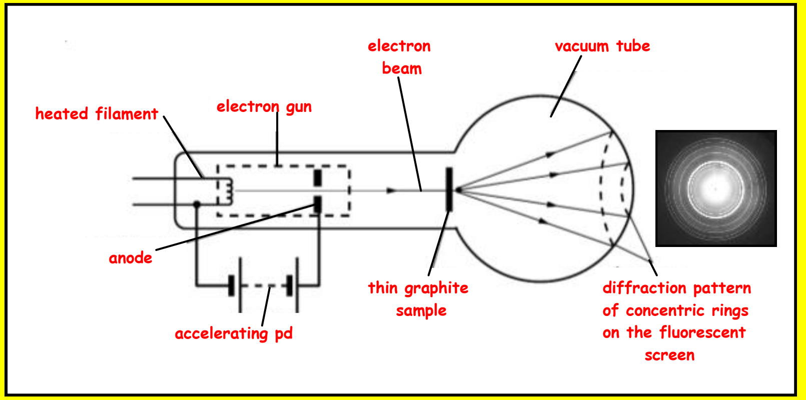
Count Louis de Broglie proposed that any particle of matter having **momentum (p = mv)** has an associated **wavelength (λ)** given by :

$$\underset{(m)}{\lambda} = \frac{h}{\underset{(kg\ m\ s^{-1})}{p}} = \frac{\overset{(J\ s)}{h}}{\underset{(kg)}{m}\,\underset{(m\ s^{-1})}{v}}$$

m = particle mass   **v = particle velocity**

'λ' is called the de Broglie wavelength.

Diffraction of Electrons



The electrons are emitted from a heated filament cathode and they are accelerated to high velocities by the large positive pd between the anode and cathode.

The **polycrystalline** graphite sample is made up of many tiny crystals, each consisting of a large number of regularly arranged carbon atoms.

The electrons pass through the graphite and produce a diffraction pattern of concentric rings on the tube's fluorescent screen.
The **de Broglie wavelength** of the electrons is of the **same order of magnitude** as the **spacing between the carbon atoms**, so this acts like a diffraction grating to the electrons.

Diffraction is a **wave** phenomenon and since these electron diffraction rings are very similar to those obtained when light passes through a small, circular aperture, they provide strong evidence for the **wave behaviour of matter proposed by de Broglie.**

Using Electron Diffraction to Study The Structure of matter

Information about the way in which atoms are arranged in a metal can be obtained by studying the patterns produced when relatively slow-moving electrons ($v \approx 10^{7}$ m s^{-1}) are diffracted after passing through a thin sample. The photograph opposite shows a typical electron diffraction pattern.

Diffraction effects are most significant **when the wavelength of the incident radiation is of the same order of magnitude as the gap or obstacle.** This also applies to electron diffraction, but in this case we are dealing with the **de Broglie wavelength.**

The separation of atoms in a metal is **~10^{-10} m,** so the diffracting electrons must be accelerated to a speed which will give them a **de Broglie wavelength of ~10^{-10} m.**

*By accelerating charged particles to higher and higher velocities, we can make their momentum greater and greater and since **$\lambda = h/p$**, this will make their **de Broglie wavelength (λ)** shorter and shorter.*

Using Electron Diffraction to Study The Structure of matter

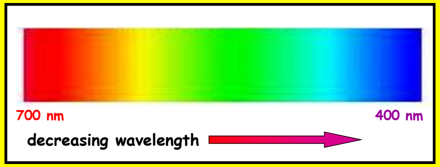
Matter can be probed more deeply by using waves of **even shorter wavelength.** Electrons accelerated to high energies of **~ 1 GeV** have a de Broglie wavelength of **~ 10^{-15} m.** When a narrow beam of such electrons is directed at a metal target, the nuclei of the metal atoms diffract the electron waves and the angle of the first diffraction minimum is used to estimate the diameter of the nucleus. This gives a value of around **10^{-15} m.**

2.5.4 ENERGY LEVELS IN ATOMS

Types of Spectra

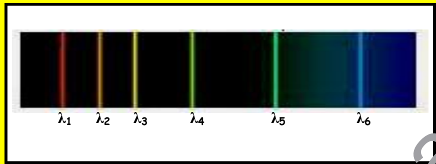
1. CONTINUOUS SPECTRUM

This is the type of spectrum obtained when **white light** is passed Through a triangular glass prism or a diffraction grating. It contains **all the visible light wavelengths** and there are no gaps in it.



2. EMISSION LINE SPECTRUM

This is the type of spectrum seen when the light from a **gas discharge tube** is viewed through a narrow slit and a diffraction grating.
It consists of **separate coloured lines** (each having it's **own unique wavelength**), on a dark background.

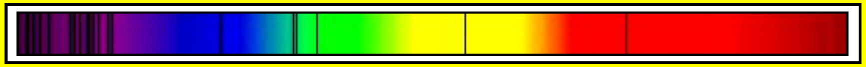


2. ABSORPTION LINE SPECTRUM

This the type of spectrum obtained when **white light has passed through cool gases**.
It consists of **black lines** on a **continuous white light spectrum** background.

The black lines are formed because the elements present in the cool gas have **absorbed certain discrete wavelengths** of the white light passing through the gas.

The Sun's Spectrum



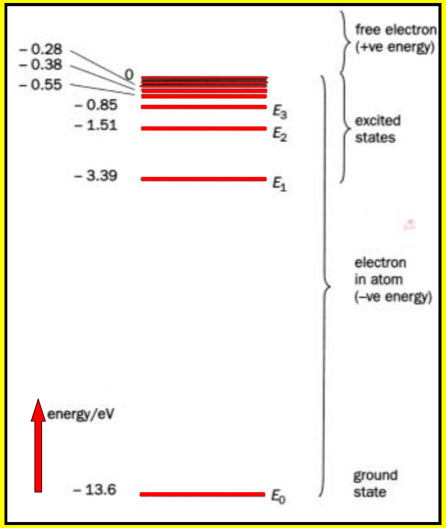
The Sun's spectrum has many dark lines (absorption spectra) which are caused when light of specific wavelengths is absorbed by the cooler atmosphere around the Sun.

The dark lines correspond to the emission lines of the various elements contained in the atmosphere through which the Sun's light passes. This is because atoms can emit or absorb at the same wavelengths.

The Origin of Line Spectra

The appearance of line spectra (i.e. lines of specific, discrete wavelength) tells us that **the electrons in atoms can only emit or absorb photons of certain fixed energies** and this means that **the electrons in an atom can only have certain fixed values of energy.**

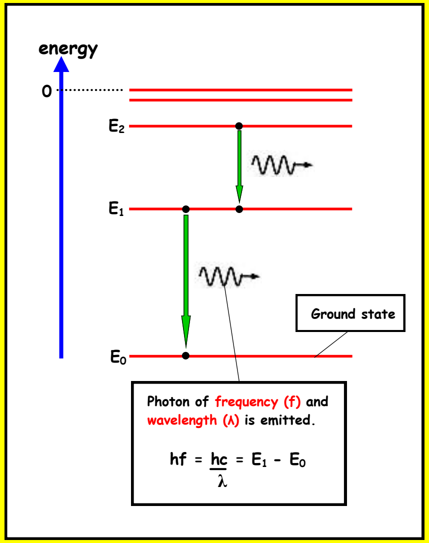
The diagram opposite shows the energy level diagram for an atom of **hydrogen.**
The electron cannot have an energy which lies in between these levels.



The energy levels have **negative values** because the electron is held within the atom by the electrostatic attraction of the nucleus and so energy has to be supplied to remove it from the atom.

Explaining EMISSION Line Spectra

An atom emits light when one of its electrons makes a transition from a higher to a lower energy level.



The energy of the emitted photon = The energy lost by the electron in the transition

= The energy difference between the two levels involved.

$$\boxed{hf = \frac{hc}{\lambda} = E_1 - E_0}$$

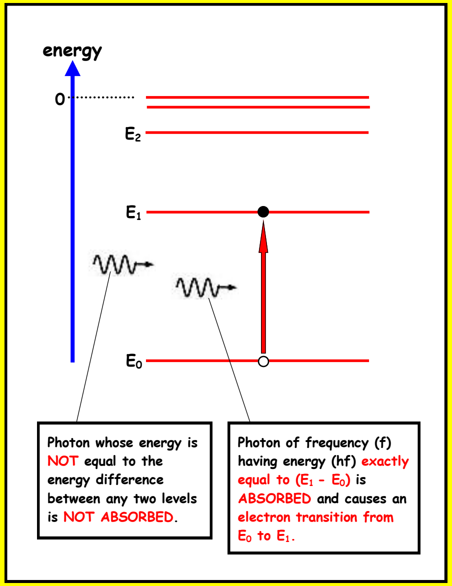
The greater the energy difference of a transition :

- The greater is the energy of the emitted photon.
- The higher is the frequency (f) of the emitted photon.
- The shorter is the wavelength (λ) of the emitted photon.

Explaining ABSORPTION Line Spectra

When white light (which consists of photons having a continuous range of energies and wavelengths) passes through a particular gaseous element, the only photons absorbed are those whose energy is exactly equal to one of the energy jumps between the various energy levels of the element concerned.

The resultant observed spectrum is then continuous, except for those particular wavelengths which have been absorbed (i.e. black lines on a continuous spectrum background).



Isolated Atoms

The atoms in a gas are considered to be ISOLATED because they are relatively far apart and so have minimal interaction with each other. As a result, DISCRETE LINE SPECTRA are obtained from hot gases.

In solids and liquids, the atoms are much closer together and so there is considerable interaction between the electrons from neighbouring atoms. This gives rise to a large number of closely spaced energy levels.

As a result, the electromagnetic radiation emitted from solids and liquids forms spectra in which there are large numbers of lines which are so close together that they appear to be bands (Called BAND SPECTRA).