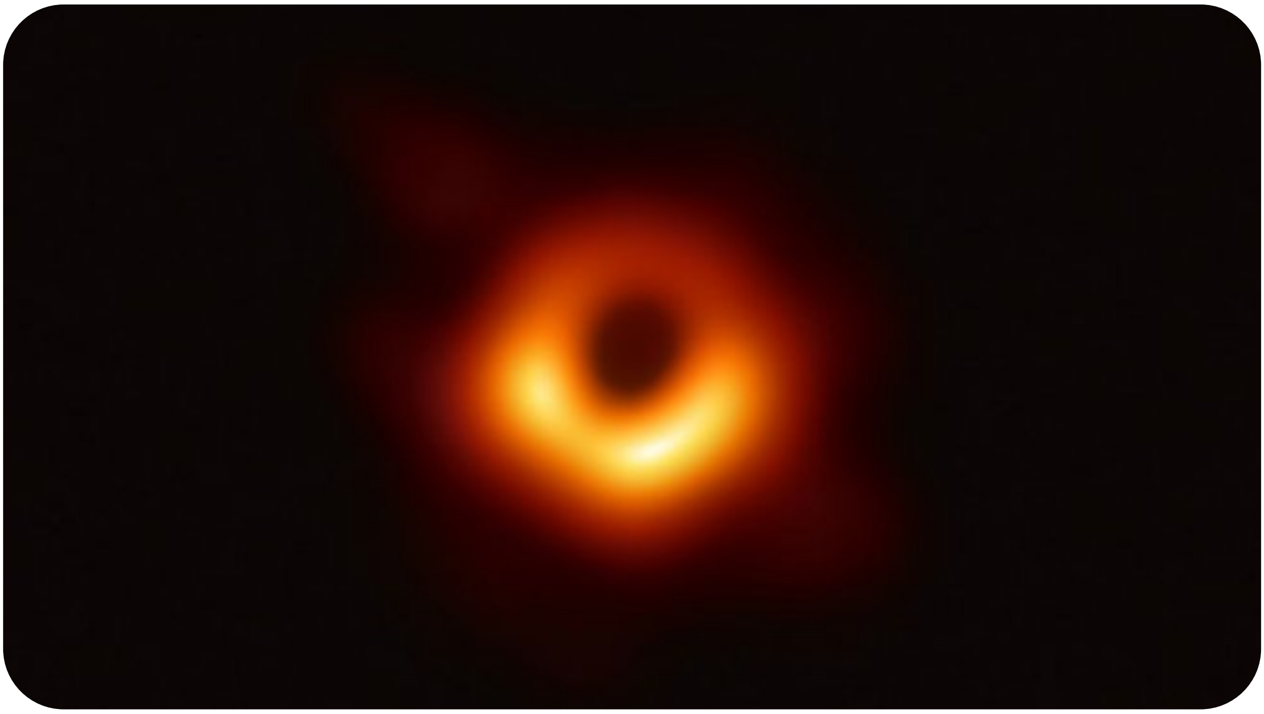
EDEXCEL International Advanced Level



# Edexcel IAL Physics Unit 2

*Summary©*


**HASAN SAYGINEL**


HS

# Waves

## 1 Nature of waves

Waves are classified into two different types:

- Mechanical waves
- Electromagnetic (EM) waves

### Mechanical waves

Waves that require a medium through which to travel. Examples include sound waves, water waves, and seismic waves.

### Electromagnetic waves

Transverse waves that combine oscillating magnetic and electric fields. EM waves do not need a medium to propagate, and so can travel through empty space.

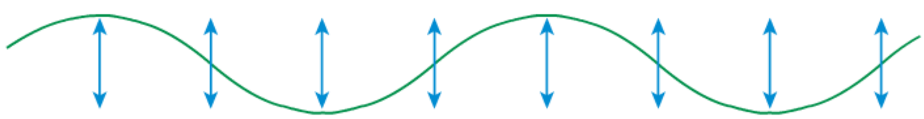
Another classification of distinguishes between;

- Transverse waves
- Longitudinal waves

### Transverse waves

A transverse wave consists of particles that oscillate perpendicular to the direction of the propagation of the wave.

In a transverse wave, the oscillations occur at right angles to the direction of travel of the wave.



### Longitudinal waves

A longitudinal wave consists of particles that oscillate parallel to the direction of the propagation of the wave.

In a longitudinal wave, the oscillations occur parallel to the direction of travel of the wave. As a result, a longitudinal wave consists of a series of **compressions** (C) and **rarefactions** (R).


### Key terms

Amplitude:is the maximum displacement from the mean position

Frequency:is the number of complete oscillations per second.

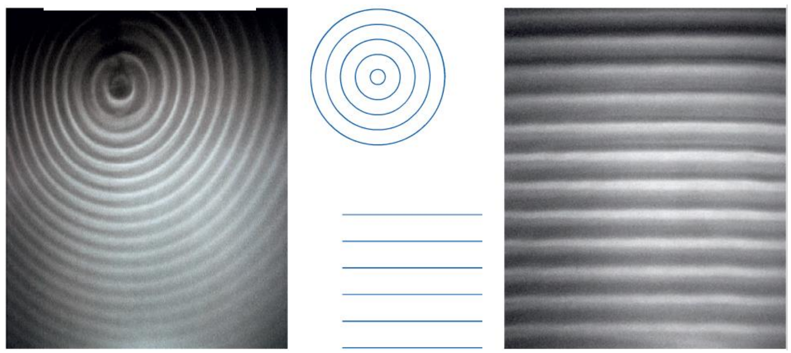
Period:is the time taken for one complete oscillation.

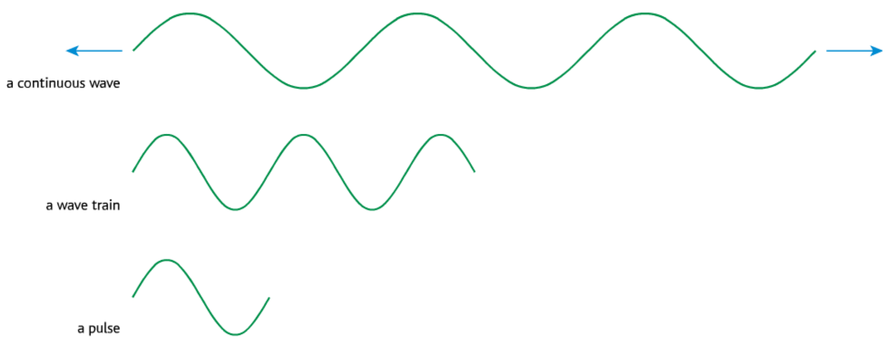
Wavelength:The distance between two points on a wave that are in phase, such as between two crests and two troughs.

## 2 DESCRIPTION OF WAVES

The way in which a wave is described in physics gives some very precise information about it.

Circularwave Plane wave






## 3 THE WAVE EQUATION

The speed of a travelling wave depends on the nature of the wave and the medium through which it is passing. However, there is a relationship between the speed, wavelength and frequency:

$$speed, v = \frac{distance}{time}$$

A wave will travel a distance of one wavelength, λ, in the time taken to complete one cycle, T:

$$v = \frac{\lambda}{T}$$

Frequency and wavelength are related by the equation:

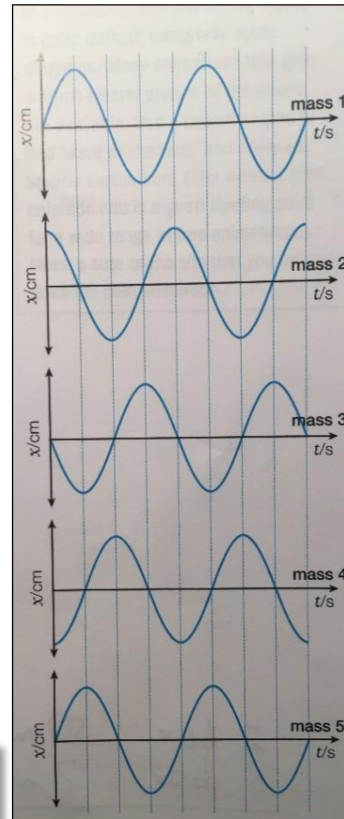
$$f = \frac{1}{T}$$

This gives: $v = f\lambda$

# 4 PHASE

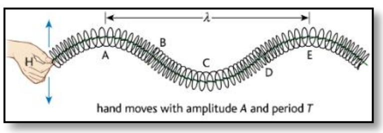
The phase of an oscillation refers to the position within a cycle that the particle occupies relative to the onset of the cycle.

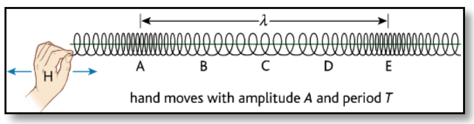
For a sinusoidal waveform, one cycle represents 2π radians (in phase), so oscillations that are in antiphase are said to have a phase difference of π radians, while those that differ by one quarter and three quartersof a cycle are $\frac{\pi}{2}$radiansand $\frac{3\pi}{2}$radians out of phase, respectively.




Making waves

All the waves are produced by oscillations of some sort. Points that are a whole wavelength apart oscillate in phase, while those that are a distance $\frac{\lambda}{2}$ apart oscillate in antiphase.




Second picture: Point A on the wave is at a point where compression is occurring- the points to the left of point A are displaced to the right of their equilibrium position, while those to the right of point A are displaced to the left of their equilibrium position. The reverse is true of point C, which is a point of rarefaction.

# 5 SOUND WAVES

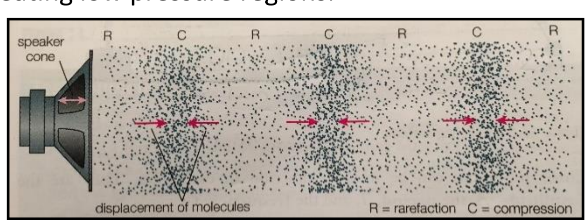
Sound is transmitted using longitudinal waves. Close inspection of the longitudinal wave in the slinky in the figure above shows the movement of tightly packed coils followed by widely spaced sections. These sections are called compressions and rarefactions. For sound waves in a gas, they create high and low pressure regions.

- High pressure regions = Compressions

Molecules to the left of equilibrium position are displaced to the right of their equilibrium position, while those to the right are displaced to the left of their equilibrium position, creating high pressure regions.

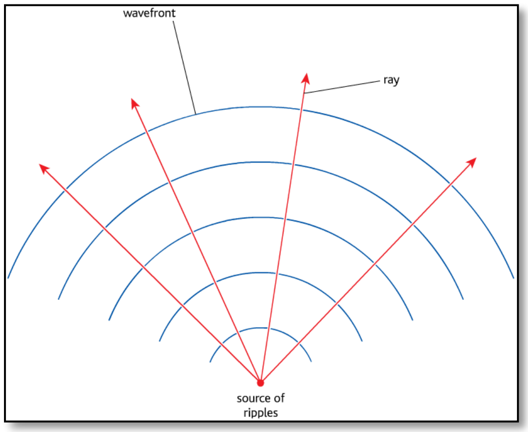
- Low pressure regions = Rarefactions

Molecules to the left of equilibrium position are displaced to the left of their equilibrium position, while those to the right are displaced to the right of their equilibrium position, creating low pressure regions.



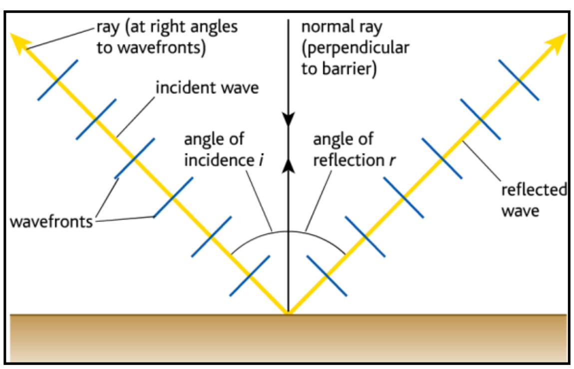
# 6 WAVEFRONTS AND RAYS

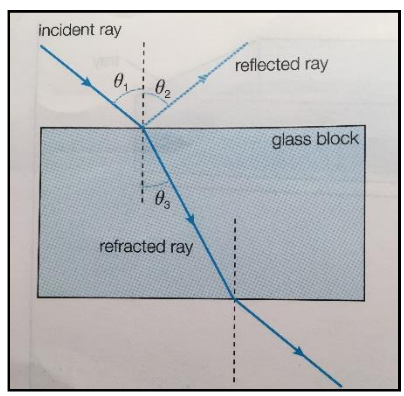
A wavefront is a line, or surface, in a wave along which all the points are in phase. Rays, on the other hand, are straight lines drawn to show the direction of travel of a wavefront. The rays are perpendicular to wavefronts.




# 7 REFLECTION

Reflection describes what happens when a wave arrives at a barrier and changes direction. The law of reflection states that the angle between the incident ray and a normal drawn at the point of reflection is equal to the angle between the reflected ray and the normal, in the plane of reflection. The fraction reflected depends on the nature of the two media and the angle at which the wave strikes the interface.




# 8 REFRACTION

Refraction is a change in direction of a wave as it passes from one medium to another due to a change in its speed. Experiments show that there is a straightforward relationship between the angle made by the incident ray with the normal ray (the angle of incidence) and the angle made by the refractive ray with the normal ray (the angle of refraction). This relationship gives a constant called the refractive index for the medium and is called Snell's law. In moving from medium 1 into medium 2, Snell's law is written as:

$$_1\mu_2 = \frac{\sin i}{\sin r}$$

### Wave speed and refraction

The change in direction, or refraction, that occurs when a wave enters a different medium is due to change in the speed of the wave. The refractive index is both a measure of how much a ray bends in moving into a different medium and is equal to the ratio of the speeds in the two media.

$$_1\mu_2 = \frac{\text{speed in medium 1}}{\text{speed in medium 2}} = \frac{v_1}{v_2} \qquad _2\mu_1 = \frac{v_2}{v_1} = \frac{1}{_1\mu_2}$$

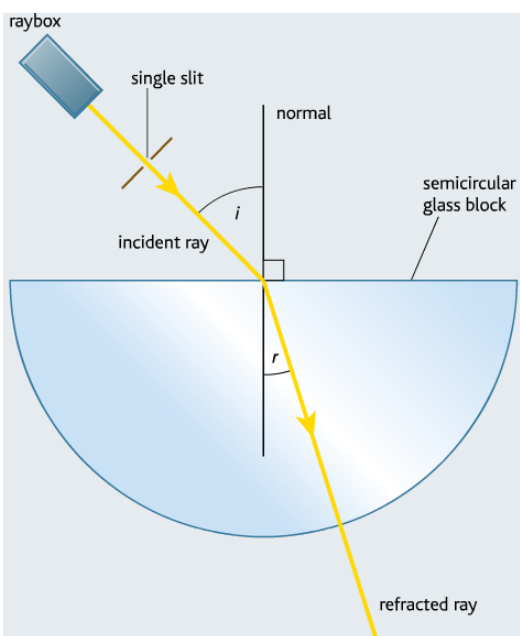
### Total Internal Reflection

When a light ray is refracted as it moves into a less optically dense medium and speeds up, it will be refracted away from normal. As the angle of incidence increases, the angle of refraction becomes larger and larger, always being greater than the angle inside the block. A time comes when the escaping ray leaves at 90°. This happens at the critical angle. If you increase the angle any further, the ray no longer leaves the glass. It is totally internally reflected, following the law of reflection.

# 9 MEASURING REFRACTIVE INDEX

Sometimes the refractive index of a material needs to be known very accurately. For example, the glass used to make spectacle lenses must have precisely known refractive index if the lens grinder is to match the lens shape to the exact power needed for a person's eye prescription.

### The experiment




The angle of incidence $i$ can be varied from 0° to 90° and the corresponding angle of refraction $r$ measured. Because the light exits the glass at 90° to the boundary (it comes from the centre of the circle of which the curved edge is a part), there will be no further bending.

The results can be analysed by plotting $\sin r$ against $\sin i$. The straight line produced will have a gradient equal to $1/_1\mu_2$.

$$_1\mu_2 = \frac{\sin i}{\sin r} \quad \text{so} \quad \sin r = \frac{\sin i}{_1\mu_2}$$

Comparing this with the equation for all straight lines:

$$y = mx + c$$

shows that the $y$-intercept should be zero and that the refractive index will be given by:

$$_1\mu_2 = \frac{1}{\text{gradient}}$$

# 10 THE PRINCIPLE OF SUPERPOSITION AND INTERFERENCE

When two or more waves meet, the total displacement at any point is the sum of the displacements that each individual wave would cause at that point. Since displacement is a vector quantity, in determining the total displacement it is important to remember to take into account whether each individual displacement is positive or negative.

The principle of superposition applies to all waves, and depends on the phase difference of the waves involved. This in turn depends upon the path difference between the waves involved. How far a wave has travelled determines its phase position, so if different waves individually travel different distances, they may be out of phase.

## Phase difference and path difference

Path difference is the difference in distance travelled by the two waves from their respective sources to a given point. When two identical waves travel different distances, they may be out of phase with respect to each other and this creates a phase difference.

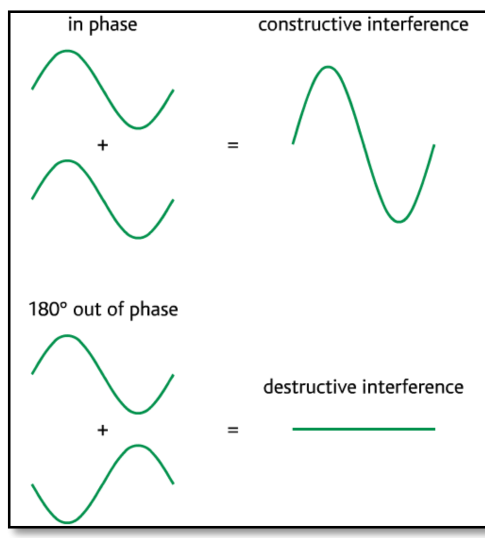
- Positions of maximum amplitude occur when the path difference is zero or a whole number of wavelengths, when the waves are always in phase, and constructive superposition takes place.

$$P.D. = n\lambda$$

- When the path difference is an odd half wavelength, the waves are π radians out of phase and the amplitude will be zero. This is destructive superposition.

$$P.D. = (n - \frac{1}{2})\lambda$$

## Interference




Interference occurs when waves overlap each other to produce a pattern where the waves reinforce each other in some places and cancel each other in others. When the waves add together to give maximumamplitude, constructive superposition occurs; when they combine to produce zeroamplitude, destructive superpositionoccurs.

Stable interference patterns occur only if:

- The waves are the same type.
- The sources are coherent.
  - Coherent:Coherent sources have the same frequency and maintain a constant phase relationship.
  - Incoherent:Waves are incoherent if the phase difference between them keeps changing.
- The waves have similar amplitude at the point of superposition.

Interference effects using light were first demonstrated at the beginning of the nineteenth century by Thomas Young.

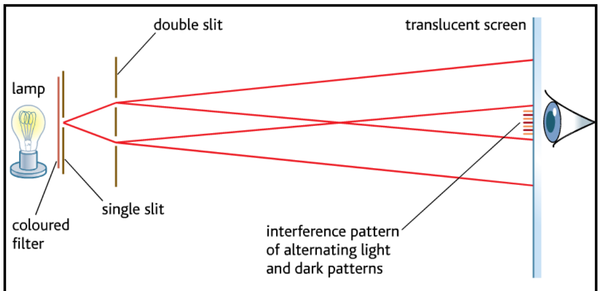
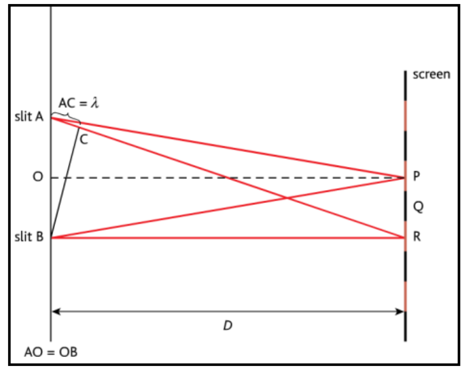



fig. 3.2.13 Young's slits experiment.




Since the light passing through the slits is from the same source, the light waves leave slits A and B in phase. Since AP=BP, the waves must arrive at P in phase, so constructive interference occurs and a bright area is seen.

AR = BR + λ → Bright area (in phase)

AQ = BQ + λ/2 → Dark area (in antiphase)

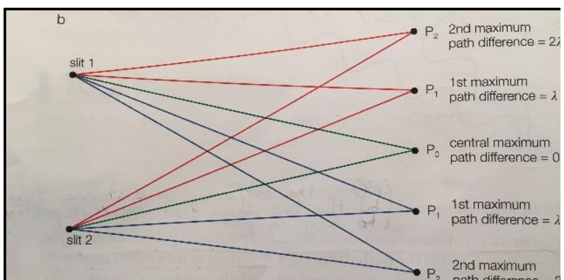



**Figure 16.5** a) Apparatus for creating double-slit interference of microwaves and b) resultant path differences.

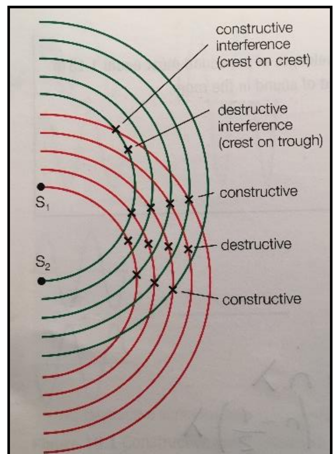
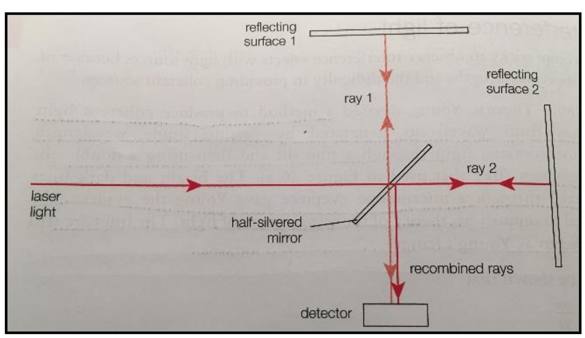



**Figure 16.4** Ripple tank interference.

## Interferometers

Interferometers use the patterns created by the recombination of a laser beam that has been split into two separate beams. Small changes in the path difference are detected by a shift in the fringe pattern.



# 11 POLARISATION

In contrast to superposition, which is something all waves exhibit, the phenomenon of polarisation is something that onlytransverse wavesshow. Longitudinal waves cannot be polarised. A wave in which the oscillations take place in a number of planes is called unpolarised, while a wave in which the oscillations occur in one plane only is said to be plane polarised in that direction.

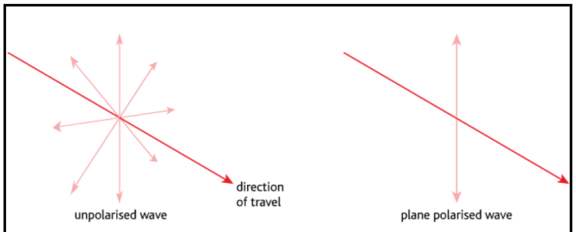


fig. 3.2.19 In an unpolarised wave, oscillations may occur in any plane, while in a plane polarised wave they occur in only one plane.

Light as a transverse wave, consists of varying electric and magnetic fields at right angles to its motion.

- In unpolarised light these variations take place in all planes at right angles to the direction in which the ray of light is travelling.
- In plane polarised light, the variations in electric field take place only in one plane. The variations in magnetic field are in a plane at right angles to this.

Light waves can be polarised in a number of ways:

- Polarising filters:In polaroid, long molecules are lined up so that only light waves oscillating in a particular plane can pass through. Two polaroid pieces that have the molecules aligned 90° to each other will not allow any light through.
- Reflection: Unpolarised light sources produce equal vertical and horizontal rays. When light hits a reflecting surface, vertical waves are refracted while horizontal waves are reflected. The amount of polarisation depends on the angle of reflection and the refractive index of the surface.
- Scattering: The sky seems blue because the short-wave region of the visible spectrum is scattered much more than the red.
- Optical activity: Optically active substances such as sugar solutions rotate the plane of polarisation by an amount proportional to their concentration and the depth of liquid through which the light travels. This can be used to measure the concentration of sugar solutions.

# 12 ELECTROMAGNETIC SPECTRUM

Electromagnetic waves are created when charged particles are accelerated, whereas mechanical waves are initiated by vibrating objects. EM waves consist of interlocking electric and magnetic fields. They oscillate in perpendicular planes to each other. A charged particle creates an electric field. When it accelerates, its electric field oscillates and produces a magnetic field.

- Electric field, which oscillates, produces magnetic field.
- Magnetic field, which changes, produces electric field.

Both fields fluctuate in time and an EM wave is thereby produced.

EM waves can also occur as a result of quantum jumps of electrons in atoms or from excited nuclei. The waves produced in this manner are emitted as photons, which are bundles of waves.

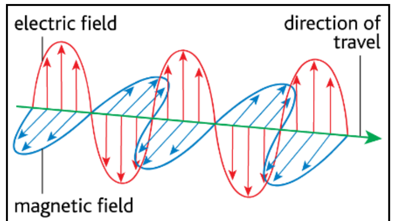


fig. 3.3.1 **James Clerk Maxwell's model of an electromagnetic wave.**

| Type of wave | Wavelength range/m | Method of production | Properties and applications |
|---|---|---|---|
| γ rays | $10^{-16}$–$10^{-11}$ | excited atomic nuclei fall to lower energy states | highly penetrating rays<br>used in medicine to destroy tumours, for diagnostic imaging and to sterilise instruments |
| X-rays | $10^{-14}$–$10^{-10}$ | fast electrons decelerate after striking a target | similar to γ rays but the method of production means that their energy is more controllable<br>used in medicine for diagnosis and therapy and in industry to detect faults in metals and to study crystal structures |
| ultraviolet | $10^{-10}$–$10^{-8}$ | sources: the sun, electric archs, special lamps | stimulates the production of vitamin D in the skin, which results in a tan<br>makes some materials fluoresce<br>used in fluorescent lamps and to detect forged banknotes |
| visible light | $4–7 \times 10^{-7}$ | electrons in atoms raised to high-energy states by heat or electric fields fall to lower permitted energy levels | light focused onto the retina of the eye creates a visual image in the brain<br>can be detected by chemical changes to photographic film and electrical charges on the charge-coupled devices (CCDs) in digital cameras<br>essential energy source for plants undergoing photosynthesis |
| infrared | $10^{-7}$–$10^{-3}$ | | radiated by warm bodies<br>used for heating and cooking and in thermal imaging devices |
| microwaves | $10^{-4}$–$10^{-1}$ | high-frequency oscillators such as a magnetron<br>background radiation in space | energy is transferred to water molecules in food by resonance at microwave frequencies<br>used in mobile phone and satellite communications |
| radio | $10^{-3}$–$10^{5}$ | tuned oscillators linked to an aerial | wide range of frequencies allows many signals to be transmitted<br>groups of very large radio-telescopes can detect extremely faint sources in space |

# 13 STANDING WAVES

Waves can be classified into progressive and stationary waves.Progressive wavesare waves in which the positions of peaks and troughs are moving. Stationary waves are also known as standing waves. In such waves, the positions of the peaks and troughs are not moving.

Standing waves are created by the superposition of two progressive waves of equal frequency and amplitude moving in opposite directions. Speakers facing each other would produce a standing wave.

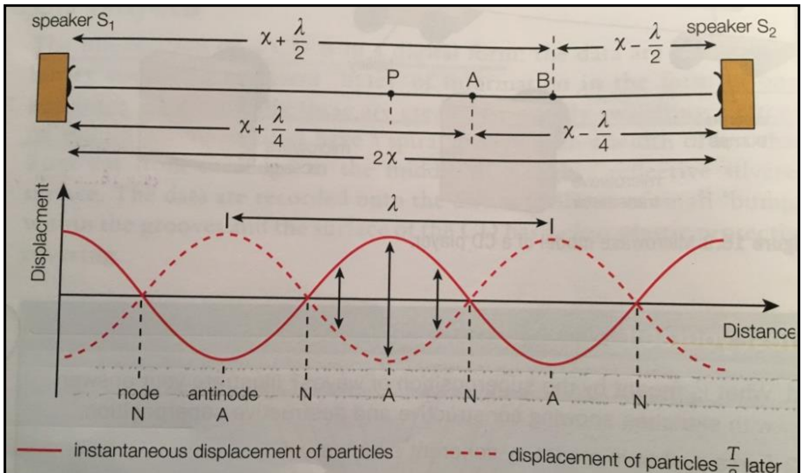



**Figure 16.10** Formation of standing wave.

- P is the midpoint. P.D. = 0, thus the waves are in phase
- At A, P.D. = half a wavelength, thus the waves are in antiphase and destructive interference occurs.
- At B, P.D. = λ, thus the waves are in phase

The points of zero amplitude are called nodes and the maxima are called antinodes. The separation of adjacent nodes and antinodes are always half a wavelength.

Standing waves differ from progressive waves in the following ways.

- Standing waves store energy, whereas progressive waves transfer energy from one point to another.
- The amplitude of standing waves varies from zero at nodes to a maximum at the antinodes, but the amplitude of all the oscillations along a progressive wave is constant.
- The oscillations are all in phase between nodes, but the phase varies continuously along a travelling wave.

## Standing waves in strings

The formation of a stationary wave on a string relies on the reflection of a progressive wave at the ends of the string. It also depends on the fact that such a reflection gives rise to a phase change of 180°.

- This phase change on reflection occurs only where a hard reflection occurs, where the string is connected to a massive solid object.
- Where the string is joined to a light object reflection also occurs at the boundary between them, but with no phase change.

Other waves behave in the same way as waves on a string.

## Stringed instruments

Stringed instruments all produce stationary waves on strings stretched between two points. When the string is plucked at its midpoint, the waves reflected from each end will interfere to set up a standing wave in the string. As both ends are fixed, they must be nodes, so the simplest standing wave will have one antinode between two nodes.

Using the expression, $v = \sqrt{\frac{T}{\mu}}$, and $v = \lambda f$, the frequency of the note emitted by the wire in this mode will be: $f = \frac{1}{2l}\sqrt{\frac{T}{\mu}}$. This equation tells the frequency is greater for:

- Shorter strings
- Strings with greater tension
- Strings that have a lower mass per unit length.

## Overtones and harmonics

The fixed ends of vibrating strings must be nodes and the simplest standing wave has a single antinode at the midpoint, as mentioned. The frequency of the note emitted from such a wave is called the fundamental frequency of the string. The fundamental vibration has the longest wavelength and the others reduce in sequence. The notes emitted by vibrations other than the fundamental are called overtones. Overtones that have whole number multiples of the fundamental frequency are harmonics.

Given that a string is fixed on both ends, it can be shown that the only waves possible on the string are those where:

$$\lambda = \frac{2l}{n}$$

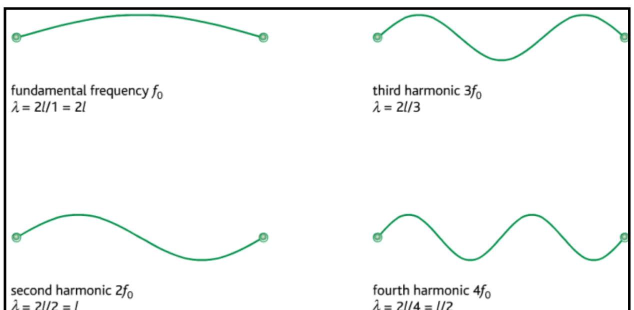
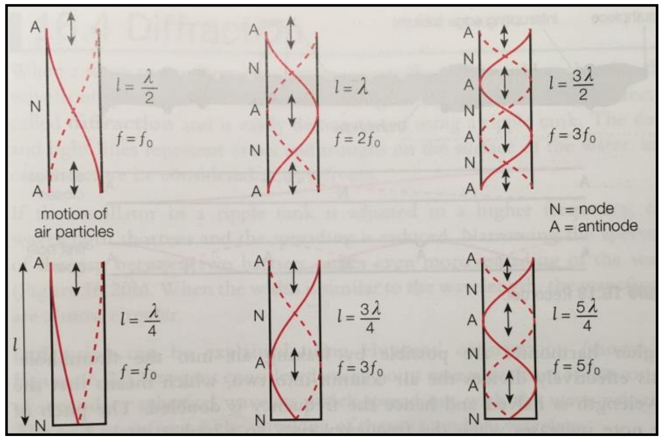



fig. 3.1.17 The first four modes of vibration of a stretched string. Notice that the distance between adjacent nodes or antinodes is always $\lambda/2$, and that there is always a node at each end of the string.

where l = the length of the string and n is a whole number

This means that nodes will occur on the string at a distance of 0, $\frac{\lambda}{2}$, $\lambda$, $\frac{3\lambda}{2}$ from the end of it and that neighbouring nodes are separated by a distance of $\frac{\lambda}{2}$, as are neighbouring antinodes. It also means that the fundamental mode of vibration of a string is an oscillation with a wavelength twice the length of the string.

## Wind instruments




Wind instruments are basically tubes in which standing air waves are formed from vibrations produced in a mouthpiece. Unlike strings, the wave boundaries can be nodes or antinodes.

At the open end, the reflections always create antinodes. At the closed ends, where the particles are unable to oscillate, nodes are formed. The fundamental frequency of an open-ended pipe is therefore twice that of the closed pipe.

# 14 DIFFRACTION

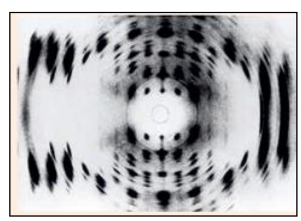
When a wave passes through a gap or is partially obstructed by a barrier, the wavefront spreads out. The amount of diffraction that occurs depends on the relationship between the size of the gap or the object and the wavelength of the wave – when the two are similar in size, substantial diffraction occurs and the wavefronts are almost circular.

## Huygens' Construction

This scientist explained the spreading out of a wave from a point source by considering each point on a wavefront as the source of a new set of disturbances. Huygens' construction is an explanation for the way in which a circular wave spreads out, eventually leading to a plane wave as the radius of the circular wave becomes very large.

# 15 THE NATURE OF ELECTRONS

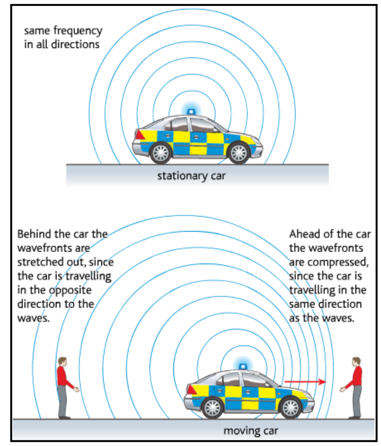
X-rays can be used to explore the arrangement of atoms within solid materials. The layers of atoms within solid materials can act as a series of gaps or slits. The X-rays first diffract as they pass through the gap. Superposition of X-rays from different layers will then produce an interference pattern. If there is a regular pattern, then the atoms in the solid are regularly structured.



Electrons can also be used to investigate materials. When a beam of electrons is directed at a crystal, a pattern like that shown can be observed.

The electron beams must have diffracted through the layers of atoms in the crystal, which suggests that electrons behave like waves. For significant diffraction, the wavelength of the wave must be of a similar size to the gap the wave is passing through. Thus, to achieve electron diffraction by passing them through the gaps between atoms in a crystal, the electron wavelength must be of the order of $10^{-10}$ metres. Electrons were initially thought to be particles, but diffraction experiments confirmed that they can also behave like waves.

# 16 THE DOPPLER EFFECT




The Doppler effect describes changes in the frequency and wavelength of waves caused by the relative movement of source and detector. It explains why the siren of a fire engine sounds in higher pitch as it comes towards us, then sounds lower after the vehicle has driven past.

When a source of sound waves moves towards an observer, each successive wave emitted comes from a position closer to the observer, who hears it more quickly due to the shorter travel time. Effectively, the waves bunch together creating an increase in frequency. Conversely, when the wave source moves away, successive waves are emitted from greater distance. The waves stretch out, making their frequency drop.

# 17 PULSE – ECHO DETECTION

Some animals such as bats and dolphins have echolocation. The bat will make a chirp through its nose. This sound pulse will be reflected back from nearby objects to the bat's sensitive ears and its brain can accurately measure the time between pulse emission and echo reception. The bat's brain has also evolved to instinctively calculate the distance to the reflecting object using the equation: $d = vt$

We have developed similar technologies. Waves reflect from a boundary between two media. The greater the difference in density between two materials, the stronger the reflection. Pulse – echo techniques are used to detect the position and/or the motion of a boundary between two materials. *A pulse is required so that the time interval between the incident pulse and the reflected pulse can be measured.

# 18 ULTRASOUND

Ultrasound is sound waves with frequencies above the threshold of human hearing. An ultrasound scan of a fetus is usually taken at about 12 weeks. Reflected pulses of ultrasound are used to determine where the boundaries are between different tissues and then build an image.

The resolution can be improved by reducing the wavelength of the sound used. Resolution can also be improved by using pulses of very short time interval. Note that shorter waves are absorbed more readily and the useful range is reduced.

Doppler ultrasound

If the ultrasound pulse in a medical scan were to encounter a moving reflector, flowing blood for example, it would be reflected so the position could be determined. However, there would be a Doppler shift in the frequency of the sound waves being used. If the Doppler shift is measured, then the speed of movement of blood could be calculated.

# 19 ISSUES WITH ANTENATAL SCANNING

Antenatal scanning of babies is now a routine part of pregnancy in many counties. Antenatal scanning using X-rays is not permitted because these waves are known to be a cause of cancer with extensive exposure. Might the same not be true of ultrasound?

Very few scientific studies were done to discover the long-term effects of ultrasound exposure. Only recent studies have shown some bad effects including, lower birthweight babies, premature births and infants taking longer to develop speech.

When developing and trialing new medical techniques, doctors must decide whether the benefits of the new technique outweigh its possible harmful consequences.

# Nature of light

## 1 History of light

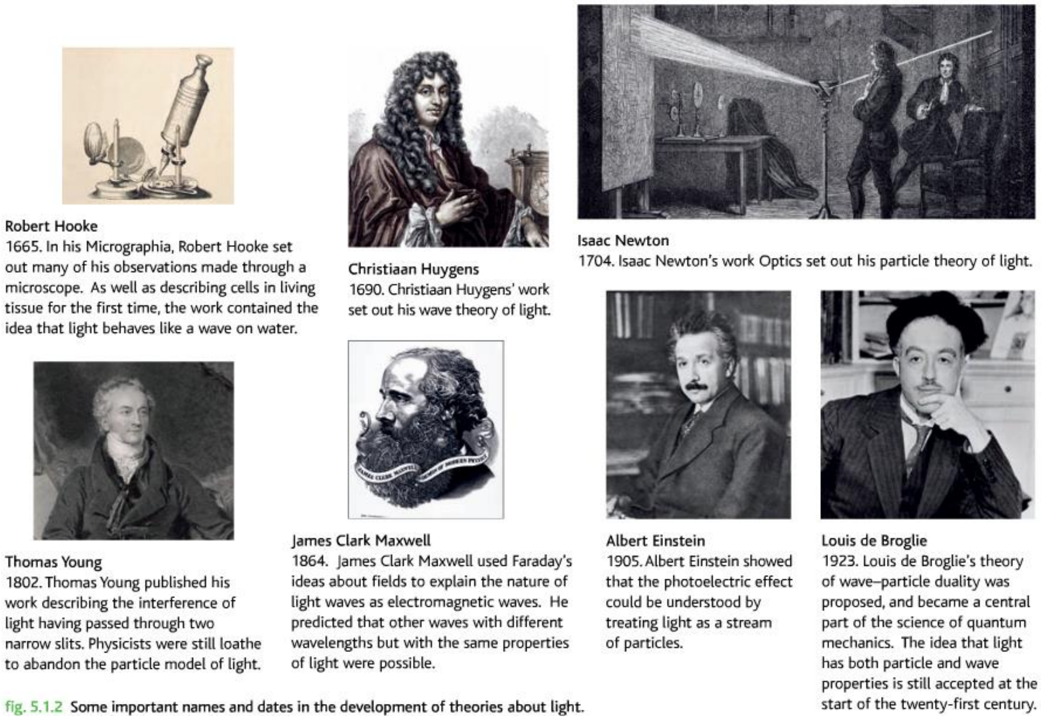



fig. 5.1.2 Some important names and dates in the development of theories about light.

## 2 The behaviour of light

Max Planck was trying to obtain a theoretical model to understand the way in which a black body emits electromagnetic radiation. A black body is a perfect emitter and absorber of electromagnetic radiation, capable of absorbing and radiating all wavelengths. He found that this was impossible unless he made an assumption that ran completely contrary to the laws of physics known at the time. He had to assume that energy could be absorbed and radiated by a body only in discrete quantities. Einstein showed that the radiation from a black body could be understood more simply if it was assumed that the radiation itself was quantised, consisting of particle-like packets of energy. Each packet is called a photon.

The behaviour of light can be modelled as a wave or as a photon and these two are linked by the following relationship. If the frequency of a wave is f, the energy of the photons in it is given by the relationship:

$$E = hf$$

where h is Planck's constant and has a value of $6.63 \times 10^{-33}$.

Radiation flux

If we know the energy of each photon in abeam, and the number of photons in the beam, we can calculate the rate that it delivers energy. How intensely light shines on something is measured by the quantity radiation flux, which is a measure of the amount of energy landing on unit area in a unit time. Energy in a unit time is the definition of power, which means that radiation flux F is defined as the power P per area A:

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

Thus, the unit for radiation flux is W m$^{-2}$.

The fact that light behaves like a wave under some circumstances and like a particle under others demonstrates that neither the wave model nor the particle model of classical physics is adequate for understanding the behaviour of light. For a full understanding of light we have to regard it as a wavicle, a wave-particle object that behaves sometimes like a classical wave and at other times like a classical particle – and other times like a mixture of the two!

# 3 THE PHOTOELECTRIC EFFECT

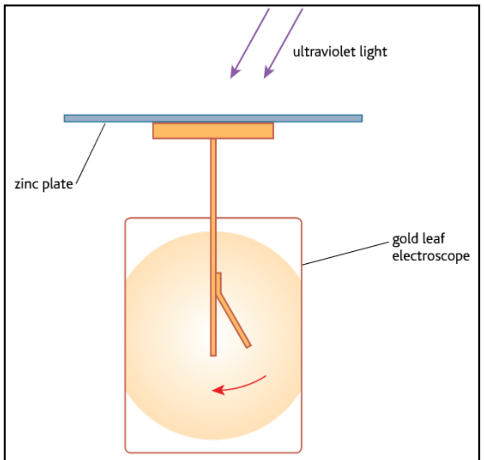


fig. 5.1.5 The leaf on a negatively charged gold leaf electroscope slowly falls if a zinc plate resting on the cap of the electroscope is irradiated with ultraviolet light.

An investigation like this shows an a number of interesting features:

- With no light falling on the zinc plate, the leaf falls only very slowly if at all (due to charge leaking away).
- Ultraviolet light shone onto the plate causes the leaf to fall rapidly. This fall is stopped if a sheet of glass is placed between the zinc plate and the ultraviolet lamp (glass absorbs UV light strongly).
- The rate of fall of the leaf depends on the distance of the lamp from the plate. The closer the lamp, the more rapid the fall.
- Visible light has no effect on the behaviour of the leaf.
- A positively charged electroscope is unaffected by ultraviolet light.

Conclusion: Ultraviolet light is capable of transferring sufficient energy to electrons in a metal so that they could escape. Electrons liberated this way are called photoelectrons.

- Photoelectrons: Electrons emitted from the surface of a metal as a result of interaction between light and the electrons in the metal.
- Photoelectric effect: The emission of electrons from the surface of a metal when a beam of light of sufficient energy is shone on the metal.

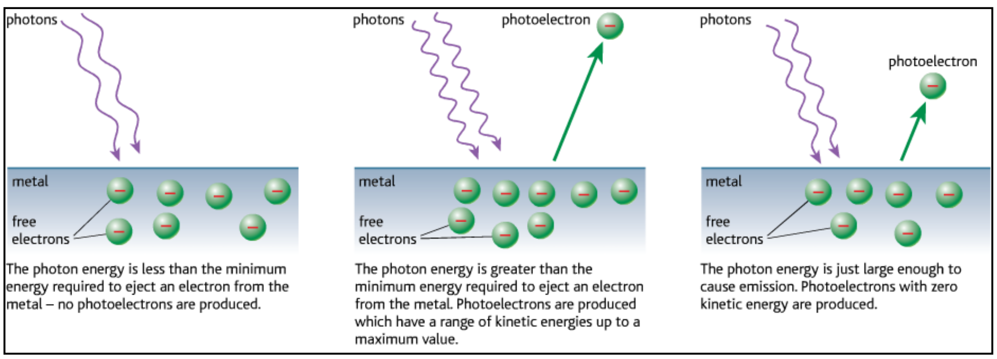
**Despite being much more intense and therefore having more energy than UV light, how can we explain why visible light cannot liberate photoelectrons?**

Einstein was able to show that a complete explanation of the photoelectric emission of electrons is possible if is light assumed to be quantised. **When photons of light strike the surface of the metal, one may strike the electron.** As a result of this collision the photon's energy may be transferred to the electron, and it may now have sufficient energy to escape from the metal. The emission of photoelectrons from a metal surface and their subsequent kinetic energy both depend on the frequency of the incident light. For a given surface there is a minimum frequency below which no emission of photoelectrons occurs.

Threshold frequency ($hf_0$): The minimum frequency of light that will release a photoelectron from the surface of a metal.

- This accounts for visible light having no effect on the electroscope. (Visible light has a lower frequency than the threshold frequency.

An electron absorbs energy from an incident photon in order to escape from the metal. Any energy remaining after the electron has done the work necessary to escape from the metal remains as the electron's kinetic energy.




Einstein's photoelectric equation expresses these ideas mathematically.

$$hf = \phi + \frac{1}{2}mv_{max}^2$$

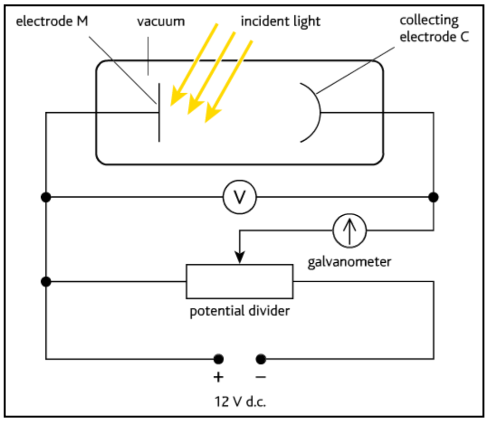
The photon energy is given by $hf$ as already mentioned, and $\frac{1}{2}mv_{max}^2$ is the maximum kinetic energy of the photoelectron. The quantity $\phi$ is the work function of the metal surface.

Work function: In the photoelectric effect, the energy required to remove an electron completely from the surface of a metal. It is equal to Planck's constant multiplied by the threshold frequency. $\phi = hf_0$

# 4 Electronvolt

An electronvolt is the work done on (or the energy gained by) an electron when it moves through a potential difference of 1 volt. When considering energy and sub-atomic particles it is convenient to use a unit of energy called the electronvolt (eV). 1 eV = $1.6 \times 10^{-19}$ J

# 5 STOPPING VOLTAGE




The investigation of the photoelectric effect may be carried out using the apparatus. Light of a known frequency is shone onto a metal electrode M. Photoelectrons from M travel towards a collecting cathode C and then flow round the external circuit.

If a metal surface is connected to a positive potential, the photoelectron is attracted back to it. To escape from the surface, the kinetic energy of the photoelectron is used to do work against electrostatic force. If the potential is increased, eventually even the most energetic electrons fail to escape, and the potential is called the stopping voltage, $V_S$.

Stopping voltage: For photoelectrons, the value of the stopping potential allows the maximum kinetic energy of the photoelectrons to be calculated.

$$\frac{1}{2}mv_{max}^2 = eV_S$$

$$hf = \phi + eV_S$$

Hence, $hf = hf_0 + eV_S$

This can be rearranged in the form of the general equation of a straight line.

$$V_S = \left(\frac{h}{e}\right)f - \left(\frac{hf_0}{e}\right)$$

So a graph of $V_S$ (y-axis) against $f$ (x-axis) will have gradient h/e and intercept $-hf_0/e$.

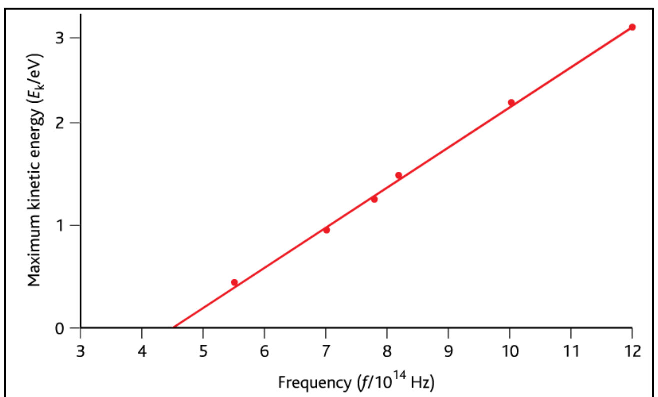



fig. 5.1.7 This graph shows the maximum kinetic energy for photoelectrons emitted from caesium by light of different frequencies. The energy is given in units of electronvolts (eV).

The graph shows how the maximum kinetic energy of photoelectrons emitted from the surface of caesium varies with the frequency, f, of the incident electromagnetic radiation.

Rearranging,

$$hf = \phi + \frac{1}{2}mv_{max}^2$$

gives,

$$\frac{1}{2}mv_{max}^2 = hf - \phi$$

So, h will be the gradient of the graph and $-\phi$ will be the intercept.

# 6 ATOMIC SPECTRA

## Types of spectra

Different wavelengths of electromagnetic radiation form a complete spectrum as already mentioned. A spectrometer is a device that can separate the wavelengths in a beam of radiation, to show those wavelengths that are present. There are two different types of spectra:

- Emission spectra
  - Line spectra
  - Continuous spectra
- Absorption spectra

Emission spectra: Spectrum of frequencies of electromagnetic radiation emitted when the electrons in an atom make a transition from a high-energy state to a lower-energy state.

Line emission spectra consist of a set of coloured lines against a dark background, each line being a particular wavelength of light emitted by the source. These lines also extend beyond the visible spectrum in many cases. The line spectrum from a sample of an element is characteristic of that element, and can be used for identification purposes.


The continuous range of colours seen in continuous spectra can be observed using light from a tungsten filament lamp. This type of spectrum was first produced by artificial means by Sir Isaac Newton, using a prism. Unlike line spectra, continuous spectra cannot be used to identify their source, although the wavelength of maximum intensity of the spectrum is linked to the temperature of the source.


Absorption spectrum is due to the absorption of light by a sample and instead of coloured lines on a dark background, it consists of dark lines at the place of coloured lines on a coloured background for a given element.


## Solar spectrum

The presence of dark lines in the spectrum of sunlight means that there is strong absorption of particular wavelengths. These wavelengths correspond to the lines in the emission spectra of hydrogen and helium. This shows the presence of these elements in the mantle of hot gas around the Sun.

# 7 ATOMIC ELECTRON ENERGIES

**Why do the spectra of elements only show emission and absorption of light at particular wavelengths?**

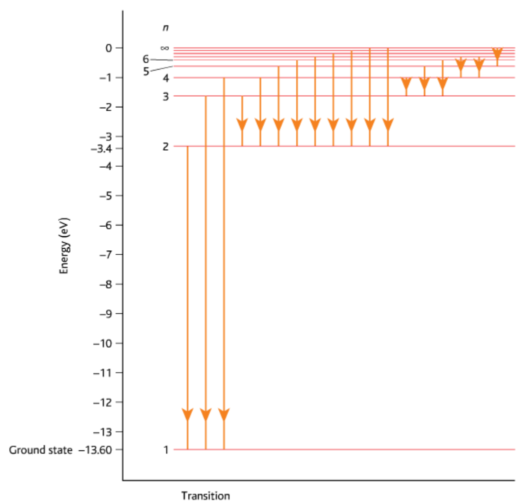
From the photoelectric effect and Einstein's photon theory, we know that a photon with a particular wavelength represents a fixed amount of energy. So each line in an emission spectrum corresponds to the atom losing a fixed amount of energy, given out as a photon of light. When an electron drops from a higher energy level, it gives out the energy difference in the form of one quantum of radiation, hf.

$$E = hf$$

This relationship is used to calculate the frequency of radiation that is emitted in a transition across a known energy band gap or between known energy levels.

Energy-level diagram of hydrogen

The element hydrogen consists of one proton and one electron.




The shortest wavelength in the hydrogen spectrum is 9.17 x $10^{-8}$ m, and this light also has the highest frequency. ΔE is given by:

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

$$E = \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{9.17 \times 10^{-8}}$$

$$= 2.17 \times 10^{-18}\,\mathrm{J}$$

$$= 13.6\,\mathrm{eV}$$

As this is the largest energy change in the spectrum, it must correspond to the electron moving from a state where the atom has the most energy to one where it has the least.

- The state in which the atom/electron has least energy is n = 1, called the ground state.
- The state in which the atom/electron has most energy is n = ∞.

The same amount of energy, 13.6 eV, is absorbed by a hydrogen atom when it is ionised from its ground state. Ionisation energy is the energy that must be supplied for an electron in the lowest energy level to just escape from the atom. Ionisation → Transition from n = 1 to n = ∞.

The spectrum has many lines of longer wavelength, which correspond to electron transitions with smaller energy changes. These correspond to transitions between the intermediate energy levels. The spectral lines with the longest wavelength from a transition involving the ground state is due to a transition between the levels n = 1 and n = 2.

When the atom absorbs energy, and the electron moves from a lower energy level to a higher one (excitation), it can only absorb energy that corresponds exactly to the energy difference between two energy levels. So absorption also only occurs for fixed wavelengths of light (quantum). A quantum is a fixed, or discrete, amount of energy, $E = hf$. This is the basis of the quantum theory. This approach can explain the most important aspects of atomic spectra:

- The production of lines is due to the existence of distinct energy levels within the atom.
- A unique line is produced for each transition between any two electron energy levels within the atom, and the frequency/wavelength of that line corresponds to the energy difference between those two levels. Thus, when an electron drops from energy level $E_2$ to a level $E_1$:

$$hf = E_2 - E_1$$

- Absorption spectra are due to the absorption of light and transition of an electron within the atom from a lower energy level to a higher one.

Because the precise energy-level structure is different for each element, each element's line spectrum is a unique and identifies that element. This principle is used to determine the chemical composition of stars.

# 8 WAVE – PARTICLE DUALITY

Light and all electromagnetic radiation has properties associated with waves. These include polarisation, diffraction and interference. On the contrary, electromagnetic radiation does sometimes behave like particles – for example, the photoelectric effect and atomic spectra. So, the burning question is whether light is made of particles or waves. The answer is both!

Electrons, which are thought to be particles, could be diffracted and therefore could behave like a wave. Therefore, particles can sometimes behave like waves and waves can sometimes behave like particles (complementarity principle)! These ideas emerged from the idea of quantum mechanics. Waves and particles are linked by the formula:

$$\lambda = \frac{h}{p}$$

where $\lambda$ is the wavelength corresponding to a particle of momentum p (i.e. a particle of mass m travelling with a velocity v). The complementarity principle says that sometimes electrons have the properties of particles and sometimes the properties of waves, but never both together.

### HSW – Laser light and energy transitions

Laser light is emitted when atoms undergo similar energy transitions at the same time. This is achieved by promoting a large number of atoms to an energy level above the ground state. As an electron in one of the excited atoms jumps down from its higher energy level it emits a photon. As this photon travels past another atom in an excited state it causes the electron in this atom to jump down to the lower level. The passage of light thus stimulates the emission of radiation from other atoms producing the intense, coherent beam of light characteristic of the laser.

# 9 SOLAR CELLS TO LIGHT THE WORLD

Fossil fuels are becoming increasingly expensive as the sources run out. Their use also damages the environment, especially, leading to climate change. Sunlight on the other hand is free and a clean source of energy. Solar energy can be harnessed in a number of ways, such as photovoltaic cells to produce electricity and water heating.

### Photovoltaic efficiency

Photovoltaic cells produce an electric current through the interaction of light photons with semiconductor materials. In certain materials, like silicon, a photon may excite an electron from an energy level where it is fixed to an atom up to one in which it can move through the material as a conduction electron. These materials cost a lot and cost, in comparison with the quantity of energy derived is critically important. Thus, efficiency is crucial in determining whether people will use cells.

$$efficiency = \frac{useful\ energy\ (or\ power) output}{total\ energy\ (or\ power) input}$$

### How does society choose its energy sources?

<u>Important considerations include:</u>

- Cost
- Global energy prices
- Impacts of continuing use of fossil fuels
- Availability of materials
- Efficiency of energy sources
- National legislation and international commitments

### HSW – Remote Sensing

The photoelectric effect has practical applications in a number of areas concerned with the detection of light. In the **photomultiplier tube** a single incident photon produces a pulse of current through an external circuit as a result of a series of electron avalanches (**fig. 5.1.9**). A high gain tube may produce as many as $10^9$ electrons from a single photon.

This type of tube can be used in an image intensifying camera to obtain pictures in extremely low light levels (**fig. 5.1.10**), or in a scintillation counter used to detect ionising events. In the case of the scintillation counter the photon of light comes from a crystal of sodium iodide which emits a weak flash of light when ionising radiation passes through it.

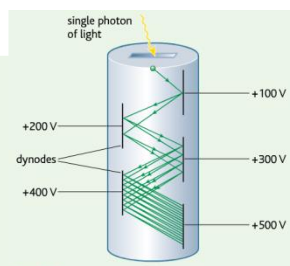



fig. 5.1.9 A single photon hitting the first electrode causes the emission of a photoelectron. This is accelerated towards the first of a series of secondary electrodes called dynodes, where further electrons are released. In this diagram each electron impact on a dynode has been assumed to cause the release of two secondary electrons.

# DC Electricity

## 1 Electric current

Electric current is the rate of flow charged particles. This can mathematically be expressed as:

$$I = \frac{\Delta \mathrm{Q}}{\Delta \mathrm{t}}$$

where I is the current and $\Delta \mathrm{Q}$ is the amount of charge flowing in time $\Delta \mathrm{t}$. Current is measured in amperes. This equation can also be expressed as:

$$\Delta \mathrm{Q} = \mathrm{I}\Delta \mathrm{t}$$

This tells us the amount of charge flowing in a certain time is given by multiplying the current with time. If a current of 1A flows for 1s, the quantity of charge flowing is said to be 1 coulomb.

### Electric charge

All matter contains electric charges and if these charges were made to move, an electric current is created. The difference between metallic conductors, semiconductors and insulators depends on the mobility of charges. All matter consists of atoms and these are made up of protons and neutrons forming the nucleus that is surrounded by a cloud of electrons. Protons and electrons have the property of charge, which gives rise to electrical forces. Under normal circumstances we do not observe any effects due to these charges, because most of the time the charges cancel out. Only when charges move in some way does their effect become apparent.

Charge is measured in coulombs. One coulomb is the amount of charge on $6.25 \times 10^{18}$ electrons, which means the charge of an electron (q) is:

$$q = 1.60 \times 10^{-19}$$

### Circuits

For an electric current to flow a complete circuit is needed. Energy is transferred to the system at one point and transferred from it at another, and appears to be carries from one place in the circuit to another by the charge carriers that move round the circuit. In metallic conductors, free electrons in metals make up the current in an electrical circuit. Electric current is not always the flow of electrons, however. For example, in an electrolyte positive and negative ions act as charge carriers.

By convention, electric current flows in the direction of the flow of positive charge, so electrons flow one way round a circuit while conventional electric current flows in the other.

# 2 ENERGY AND ELECTRICITY

Moving electric charge gives rise to an electric current. But, what makes charges move?

- A cell produces an electromotive force from its chemical energy, which creates a potential difference in a circuit. The charges in the circuit components and connecting wires experience a force, causing the charges to move round the circuit. The potential difference therefore does work on the charges, thus developing power in the circuit.

## Electromotive force (EMF)

The electromotive force of an electrical source is defined as the energy per unit charge converted into electrical energy by the source. (The amount of energy supplied to each unit of charge is called the electromotive force or emf of the cell.) The unit of emf is volt (V). A cell is said to have an emf of 1 V when it supplies 1 J of energy to each to 1 C of charge flowing through it, in other words:

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

As the emf of an electrical source is defined as the energy per unit charge converted into electrical energy, it can be expressed as:

$$emf = \frac{energy\ converted\ into\ electical\ energy}{charge\ passing}$$

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

## Potential difference

The potential difference between two points in a circuit is the electrical energy per unit charge converted into other forms of energy.

Just as the energy stored in the chemicals of a cell can cause charges to flow through a circuit, the energy carried by moving charges can cause other things such as a lamp glowing. Potential difference has the same units as emf. Remember that energy transferred is equal to work done so this gives us the definition of potential difference as work done per unit charge:

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

Remember:

- Emf and p.d. are both measured in volts, or joules per coulomb.
- Emf is the creation of electrical energy from other forms of energy.
- P.d. is the conversion of electrical energy into other forms of energy.

Note: Think of emf as being the cause and p.d. as the effect.

# 3 MEASURING CURRENT AND POTENTIAL DIFFERENCE

The current in a component can be measured by connecting an ammeter in series with the component. Ammeters have a low resistance so that they do not affect the current they are measuring.

The potential difference between two points in a circuit is measured by connecting a voltmeter between the points. They are connected across (or in parallel with) the component. Voltmeters must take some current to operate and in order to keep it as small as possible, voltmeters should have a very high resistance.

Nowadays, current and voltage sensors are often connected to a computer. Advantages include:

- Record the current and potential difference over time automatically.
- Take many more readings than a human.
- Fewer errors.
- Readings can be taken at more frequent intervals.
- Produce graph of readings quickly and easily.
- Improves reliability and validity of the data.

# 4 RESISTANCE

The resistance of an electrical component can be thought of as its opposition to an electric current flowing in it. This resistance is caused by collisions of electrons with the vibrating lattice ions as the electrons drift through the material of the conductor. As a result of these collisions, electrical energy is dissipated as thermal energy and the component heats up.

Experiments have shown that there is a simple relationship between current and p.d.:

- **Provided the temperature and other physical factors remain constant, the current through a wire is proportional to the potential difference across its ends.**

This is known as the Ohm's Law. Any electrical component for which the current is proportional to the voltage is said to be ohmic. This law is mathematically expressed as:

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

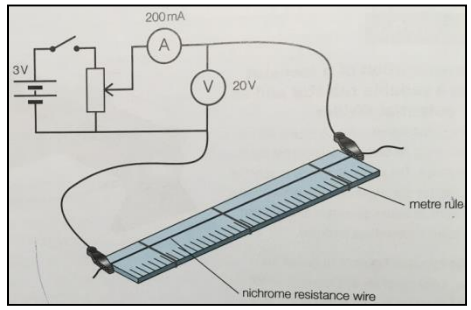
The unit of resistance is ohm (Ω) which is equivalent to V $A^{-1}$.

To show proportionality, when a graph of current against voltage is drawn it should be straight and pass through the origin. Resistance of an ohmic resistor is constant within conditions specified and thereby the gradient of the graph is constant.

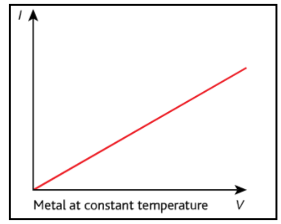
# 5 CURRENT – POTENTIAL DIFFERENCE RELATIONSHIPS

If the relationship between the current through a conductor and the pd across its ends is explored, it is possible to determine whether it is ohmic or non-ohmic. Ohmic conductors have straight I – V graphs which pass through the origin, whereas non-ohmic conductors have non-linear graphs.

### ✓ I –V characteristics for a metallic conductor



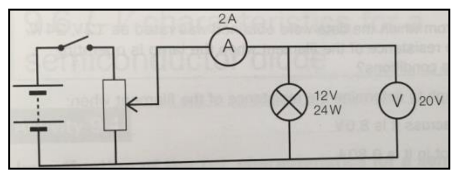

- A potential divider circuit is set up to provide variable p.d. and a 1 m length of the wire is connected to the circuit by means of crocodile clips.
    - It is important to ensure that the clips make a good connection.
- The p.d. is set to its minimum value and switched on.
- The p.d. is gradually increased and corresponding V and I values are recorded.
- The experiment is repeated with the terminals of the cell reversed.
- The p.d. across the wire and the current in the wire are now in the opposite direction to that in the first experiment and are therefore recorded as having negative values.
- The data are plotted on a set of axes.



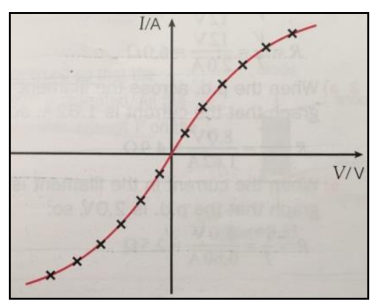

Deductions from the graph: As the graph is a straight line through the origin we can deduce that the current is proportional to the p.d. The wire therefore obeys Ohm's law, irrespective of the direction of the current.

### ✓ I –V characteristics for a tungsten filament lamp

- The circuit shown is set up with the voltage from the power supply set at its minimum value.
    - It is important to start with the power supply set to its minimum value so that the lamp starts with the lowest current and is then gradually heated up as the current is increased. It also prevents the possibility of blowing the filament of the lamp, should the voltage increase too much.

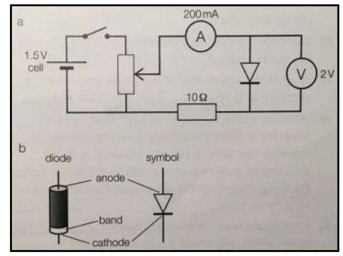



- The circuit is switched on and the p.d. is gradually increased. The p.d., and corresponding current are recorded at intervals up to a maximum p.d.
- A graph with I on the y-axis against V on the x-axis is then drawn.
- After at least five minutes have elapsed, the power supply connections are reversed.
    - Time is allowed for the filament to cool down.
- Experiment is repeated for the negative values and these are added to the graph.

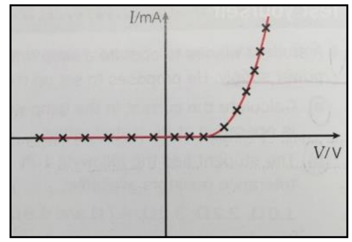



Deductions from the graph: As the current increases, the filament heats up and its resistance increases. This can be deduced from the graph by observing that the rate at which the current increases with voltage gets less as the voltage increases. This means that the resistance must be getting greater and that is because resistance is equal to the inverse of the gradient of a I – V graph.

✓ I –V characteristics for a semiconductor diode




- The circuit is set up as shown in the figure. It is essential to observe the polarity of the diode.
- The diode is said to be forward biased when connected this way around.
- The resistor is included to limit the current in the diode and prevent is being damaged.
- The circuit is switched on and the p.d. is very slowly increased. Values of I and V up to the maximum current obtainable are recorded.
- The power supply connections are now reversed so that the diode is reverse biased and the experiment is repeated. A graph of I against V is drawn.




Note: The current in the diode when it is reverse biased seems to be zero. In reality, a very small current flows, but it is so small that it is not detected by the milliammeter.

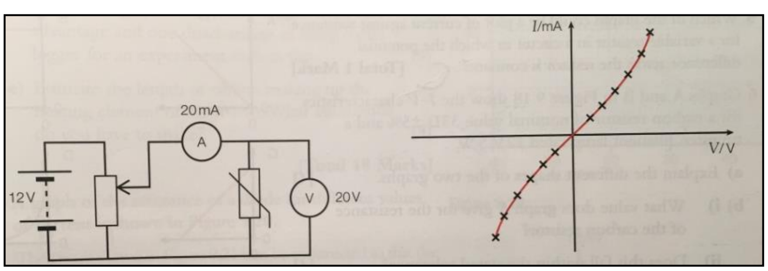
Deduction: Past a certain voltage, the resistance of a diode drops very steeply provided that it is forward biased.

✓ I –V characteristics for a thermistor

- The circuit shown is set up, with the voltage from the power supply set at its minimum value.
- The circuit is switched on and the p.d. is gradually increased. Value of I are recorded at regular intervals of p.d.
- A graph with I on the y-axis against V on the x-axis is drawn.
- After at least five minutes have elapsed, the power supply connections are reversed and the experiment is repeated, remembering to start with the minimum p.d. as before. Negative values are also added to the graph.

Deductions from the graph: Resistance values indicate that the resistance of the thermistor gets less as the current increases. This is because the current causes the thermistor to warm up and the resistance of a thermistor decreases with temperature. This is illustrated by the shape of the graph; as the current increases, the line curves upwards. This means that the rate of increase in current is increasing, i.e. the resistance is decreasing. ($V = IR$)

Note: It is not advised to use high currents because there is a danger that the thermistor may over-heat and get damaged. When the current increases, the resistance gets less and so the current will get even bigger. The temperature will therefore increase, causing a further decrease in resistance, and so an even greater increase in the current and so on… This can produce what is known as thermal runaway.



# 6 POWER AND WORK IN ELECTRIC CIRCUITS

If we consider a lamp in a circuit, the potential difference across it measures the energy transferred to the lamp per unit charge flowing through it, while the current measures the rate of flow of charge through it:

$$V = \frac{W}{Q} = \frac{E}{Q} \qquad I = \frac{Q}{t}$$

If we multiply the p.d. and the current together we get the rate at which energy is transferred to the lamp:

$$V \times I = \frac{E \times Q}{Q \times t} = \frac{E}{t}$$

The rate at which energy is transferred to an element like a lamp in a circuit is called the power dissipation. It is measured in watts. Use of relationship between V, I and R gives us two other relationships for power dissipation:

$$P = VI \text{ and } V = IR \qquad \text{so} \qquad P = (IR) \times I = I^2R$$

and

$$I = \frac{V}{R} \qquad \text{so} \qquad P = V \times \frac{V}{R} = \frac{V^2}{R}$$

Power is dissipated in a resistor, particularly if the resistor is in the form of the filament of a lamp or the element of an iron or kettle. The electrical energy transferred in the resistor increases the potential energy and random kinetic energy of the atoms of the material of a resistor. (Internal energy)

Work done (Electrical energy)

Power is the rate at which energy is transferred, so we can find out the total amount of energy transferred – or the work done – by multiplying the equation for power by time that the device operates for:

$$P = VI$$

$$P \times t = VI \times t$$

$$W = VIt$$

This is an alternative way of combining the equations that define voltage and current:

$$V = \frac{W}{Q} \qquad I = \frac{Q}{t}$$

$$Q = \frac{W}{V} \text{ and } Q = It$$

$$\therefore \frac{W}{V} = It$$

$$W = VIt$$

# 7 THE TRANSPORT EQUATION

In order for current to flow in a material, suitable charge carriers such as electrons or ions must be present within the material.

In a metallic conductor, the charge carriers are delocalised electrons. These electrons move with random thermal movement. When a potential difference is applied to a circuit, an electric field is created and exerts a force on free electrons, which causes them to drift in the direction of the force. In accordance with Newton's second law, the electrons would accelerate continuously if it were not for the fact that they collide with the regularly spaced atoms with a positive charge. These collisions cause an equal and opposite force to be exerted on electrons, which by Newton's first law, continue with a constant drift velocity, giving rise to a constant current.

As the charge carriers are electrons, which a negative charge, they drift towards the positive terminal of the cell. The conventional current, however, is in the opposite direction to the flow of electrons.

For a conductor, the current I is given by:

$$I = nAvq$$

- A = area of cross-section of conductor
- n = number of charge carriers per cubic metre
- q = charge on each charge carrier, q = 1.60 x $10^{-19}$ for electrons.
- v = drift velocity of charge carriers

Drift velocity of electrons is so slow. Despite this, when a bulb is switched on, it instantly gives light.

- This is because although the electrons themselves are travelling so slowly, the electric field that causes them to move travels at nearly the speed of light. All of the electrons start to move almost instantly.
- Secondly, although the individual electrons are moving along the wire very slowly, there is simply an enormous number of them and therefore the charge flowing per second equates to a significant current.

# 8 RESISTIVITY

Investigations show that the resistance of a uniform conductor depends on:

1-) Its length 2-)Its cross-sectional area 3-)The material of which it is made

The relationship between resistance and these quantities is given by:

$R = \frac{\rho l}{A}$, where $\rho$ is the resistivity of the material. Resistivity is measured in Ω m. According to this equation R is directly proportional to l, and inversely proportional to A. This makes sense:

If the wire is longer, it will be more difficult for the electrons to drift from one end to the other. If the wire has a larger cross-sectional area, it will be easier for the electrons to flow.

# 9 UNDERSTANDING CONDUCTION

## Conduction in metals

High thermal and electrical conductivity of metals is explained by the idea that the outermost electrons in the atoms of a metal are delocalised and form a sea of electrons which is sometimes referred as electron gas. These electrons are free to move around through the body of the metal.

Any solid is a lattice with atoms regularly arranged and bonded together. When a source of emf is connected to the ends of a conductor this causes an electric field through the conductor. This field has the effect of causing the electrons in the conductor to move with an average velocity known as the drift velocity.

- Effect of temperature on the resistivity of a metallic conductor

Resistance of metallic conductors increases with increasing temperature. This is the case in a filament lamp, where the gradient of the I-V graph is not constant.

Resistance is caused by the vibrating positive ions in the crystal lattice of the metal impeding the flow of electrons. When the temperature of the metal is raised, the amplitude of vibration of the lattice ions increases. As a result, the number of collisions of lattice ions with the conduction electrons is increased, reducing the current flow.

In terms of the transport equation, $I = nAvq$, **A and q are constant** for a given wire. For a metallic conductor, n does not depend on the temperature and so **n is also constant**. As the temperature rises, the increased vibrations of the lattice will reduce the drift velocity, v, of the electrons and so I will also decrease – that is, the resistance increases with temperature.

Metallic conductors are, therefore, referred to as having positive temperature coefficient. A material has a positive temperature coefficient if its resistivity increases when its temperature increases.

## Conduction in pure semiconductors

Semiconductors have resistivities between those of insulators and those of conductors. Pure semiconductors are usually referred to as intrinsic semiconductors. In an intrinsic semiconductor electric current is carried by moving electrons, as in metals. The number of these electrons is much less than in a conductor, however.

- Effect of temperature on the resistivity of a semiconductor

If the temperature is raised, more electrons in the semiconductor will be freed and the conductivity increases. The resistivity goes down. Thermistors are semiconductors, for example.

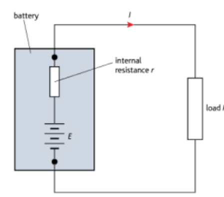
- NTC thermistors have a negative temperature coefficient. A material has a negative temperature coefficient if its resistivity. A negative temperature coefficient can also be explained using $I = nAvq$. In a semiconductor, an increase in temperature can provide extra energy to release more charge carriers. So, n increases and it increases exponentially with temperature. A and q are constant s before but n increase much more than the relatively small decrease in v. The overall effect is that I increases, so that resistivity decreases with temperature.

- In semiconductors with positive temperature coefficient, the resistance increases with increasing temperature. PTC semiconductors are achieved by doping, whereby a pure semiconductor such as germanium or silicon has atoms of impurity added to it. Doping results in an extrinsic semiconductors, because the impurity introduces extra charge carriers to the semiconductor lattice.

Note: If the temperature is high enough, even some materials that we normally think of as insulators can begin to conduct. This is because the energy associated with the very high temperature breaks down the atomic structure so that more charge carriers are released.

| Metallic conductor | Semiconductor |
|---|---|
| **n** constant | **n** increases **exponentially** |
| **A** constant | **A** constant |
| **v** decrease | **v** decrease |
| **q** constant | **q** constant |
| As a result, | As a result, |
| **I** decreases | **I** increases |
| **Resistance** increases | **Resistance** decreases |

# 10 INTERNAL RESISTANCE




Unfortunately, not all of the chemical energy converted to electrical energy inside a cell emerges at the terminals of the cell. The internal resistance of a cell, or other power supply, opposes the flow of charge through the cell. Some of the energy converted by the cell, or power supply, will be used up inside the cell to overcome this resistance. If there is a current, I, in a circuit:

| Rate of energy converted in cell | = | Rate of work done against internal resistance | + | Rate of work done lighting lamp |
|---|---|---|---|---|
| $\varepsilon I$ | $=$ | $I^2 r$ | $+$ | $I^2 R$ |
| $\varepsilon$ | $=$ | $Ir$ | $+$ | $IR$ |

Rearranging: $IR = \varepsilon - Ir$

- ➔ $V = \varepsilon - Ir$
- ➔ $I = \frac{\varepsilon}{R+r}$

# 11 PRINCIPLE OF SOLAR CELLS

When light strikes the photocell, it gives some of its energy to free electrons in the semiconductor material of the cell. An electric field within the cell provides a force on the electrons. The electron flow provides the current and the cell's electric field causes a voltage. With both current and voltage, we have power, which is the product of the two.

## 12 CURRENT IN SERIES AND PARALLEL CIRCUITS

In a series circuit, the current is the same in each component. This is because the rate at which electrons leave any component must be the same as the rate at which they enter the component – if this were not the case, electrons would be lost from the circuit, which would contravene the principle conservation of charge.

Conservation of charge: a principle stating that the total electric charge of an isolated system is fixed.

In a parallel circuit, electrons spread depending on the total resistance on each branch, so the current differs, however, total current is fixed.

Remember that charge and therefore current must always be conserved at a junction.

## 13 CONSERVATION OF ENERGY AND POTENTIAL DIFFERENCE

Conservation of energy is a fundamental concept of physics. It is stated in this way: energy cannot be created or destroyed but merely changed from one form to another.

By the principle of conservation of energy, when a charge, Q, flows round the circuit:

$$energy\ converted\ by\ battery = energy\ dissipated\ in\ the\ n\ resistors$$

$$Q\varepsilon = QV_1 + \cdots + QV_n$$

$$\varepsilon = IR_1 + \cdots + IR_n$$

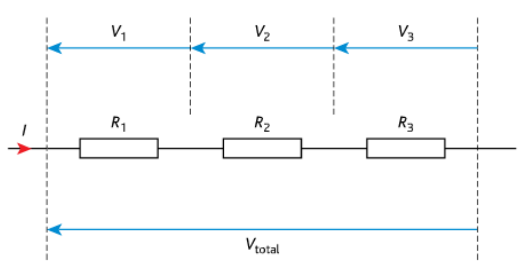
Or circuit emf, $\varepsilon = \sum IR$

## 14 RESISTORS IN SERIES AND PARALLEL

### Resistors in series

Since the three resistors are connected together in series, we know that they must all have the same current, $I$, flowing through them. We also know (from Kirchhoff's second law) that the sum of the pds across the individual resistors must be equal to the total pd across all three resistors, that is:

$$V_{total} = V_1 + V_2 + V_3$$




Dividing both sides of this equation by $I$ gives:

$$\frac{V_{total}}{I} = \frac{V_1}{I} + \frac{V_2}{I} + \frac{V_3}{I}$$

We know that Ohm's law defines the resistance of each resistor as:

$$R_1 = \frac{V_1}{I} \qquad R_2 = \frac{V_2}{I} \qquad R_3 = \frac{V_3}{I}$$

and the total resistance must be defined as:

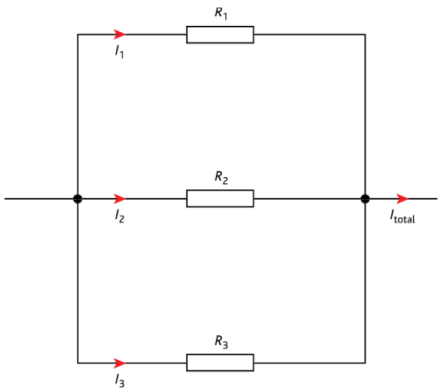
$$R_{total} = \frac{V_{total}}{I}$$

Comparing these relationships, we can see that:

$$R_{total} = R_1 + R_2 + R_3$$

This relationship applies to any number of resistors connected together in series.

Resistors in parallel




Because the three resistors are connected together in parallel, they must all have the same potential difference, $V$, across them. We also know (from Kirchhoff's first law) that the sum of the currents through each individual resistor must be equal to the current through all three resistors in total, that is:

$$I_{total} = I_1 + I_2 + I_3$$

Once again we can apply Ohm's law:

$$I_1 = \frac{V}{R_1} \qquad I_2 = \frac{V}{R_2} \qquad I_3 = \frac{V}{R_3}$$

and the total current can be calculated as:

$$I_{total} = \frac{V}{R_{total}}$$

Comparing these relationships, we can see that:

$$\frac{V}{R_{total}} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

Dividing both sides of the equation by $V$ gives:

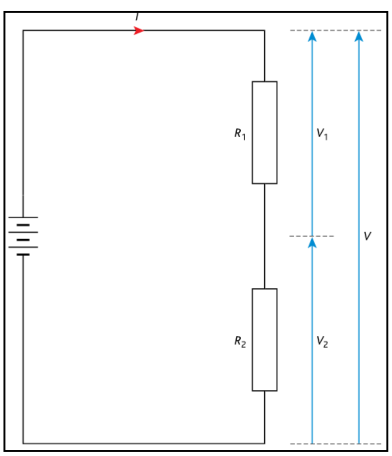
$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

This relationship applies to any number of resistors connected together in parallel.

Tip: When deriving the equations for resistors in series and parallel, remember:

- Resistors in series have the same current in each resistor.
- Resistors in parallel have the same potential difference across each resistor.

# 15 THE POTENTIAL DIVIDER




A potential divider consists of two resistor connected in series with a supply. Because they are in series, the same current flows through both resistors, and the potential difference of the supply is divided between them. Using Ohm's law:

$$V_1 = IR_1 \text{ and } V_2 = IR_2$$

Dividing the first equation by the second gives us:

$$\frac{V_1}{V_2} = \frac{R_1}{R_2}$$

,which means that the potential difference, V, across the two resistors has been divided up in the ratio of their two resistances – hence the name potential divider. By choosing appropriate values of $R_1$ and $R_2$ any voltage between zero and V can be obtained across either of the two resistors.

$$V_{out} = V_{in} \times \frac{R_2}{R_1 + R_2}$$