G482 – Electrons, Waves and Photons; Revision Notes
Module 1: Electric Current

Electric Current
- A net flow of charged particles.
- Electrons in a metal
- Ions in an electrolyte

Conventional Current
- A model used to describe the movement of charge in a circuit. Positive to negative

Electron Flow
- The movement of electrons around a circuit. Negative to positive

Coulomb
- Unit of electrical charge (C).
- 1C = 1A * 1s (Q=It)

Ammeter
- An instrument that measures electrical current
- Always connected in series
- Traditionally they used small coils that rotated in magnetic fields to detect current
- To avoid the ammeter affecting the circuit, it must have negligible resistance

Elementary Charge
- The charge on 1 electron (e) = 1.6×10^{-19}C

Kirchhoff's First Law
- The sum of the currents entering any junction is always equal to the sum of the currents leaving the junction
- $\sum I_{in} = \sum I_{out}$
- This is a consequence of the conservation of charge; electrons cannot simply appear or disappear

Mean Drift Velocity
- The average speed of charged particles along the length of a conductor
- I=nAve

Conductors, Semiconductors and insulators
- Semiconductors typically have relatively low number densities; therefore conduction electrons have more room to move in the material. This means that the electrons are less impeded when travelling (less collisions); therefore higher mean drift velocity
- Conductors have large number densities; so the conduction electrons collide with each other a lot more, resulting in a smaller mean drift velocity
- Insulators have such a small number densities, meaning fewer electrons to carry charge. Those that can must battle their way through a complex structure in the material.

Potential Difference
- Electrical energy transferred per unit charge, when electrical energy is converted into another form
- Electrical energy to light energy in a light bulb

Electromotive Force
- The energy transferred per unit charge when a type of energy is being converted into electrical energy
- Chemical energy to electrical energy in a cell

Volt
- Unit of potential difference and e.m.f (V)
- $1V = 1J\ C^{-1}$

Voltmeter
- A device for measuring p.d and e.m.f
- It measures the difference in electrical potential energy
- Always connected in parallel
- They measure the amount of energy (in joules) per coulomb across a component

Resistance
- A property of a component that regulates the electrical current through it.

Ohm
- Unit of resistance (Ω)
- $1\ \Omega = 1V\ A^{-1}$

Ohm's Law
- Law stating that current through a conductor is proportional to the potential difference across it, provided physical conditions such as temperature remain constant
- $I \alpha V$

I-V Characteristics of a Resistor at a Constant Temperature
-
  Resistor at a constant temperature

  Current (A) vs Potential Difference (V)
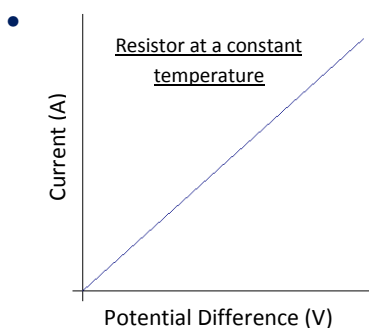
  This is known as ohmic; the current is directly proportional to the potential difference. (It obeys ohm's law)

-
 Filament Lamp

  Current (A) vs Potential Difference (V)
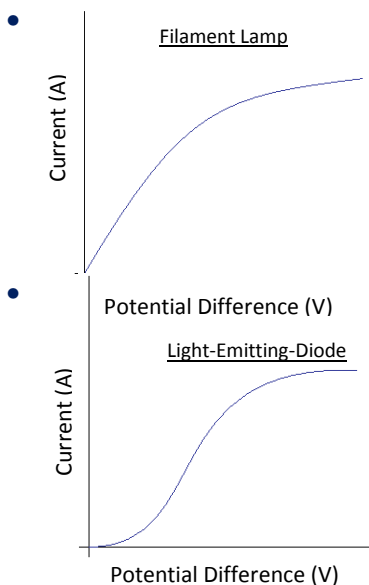
  This is known as non ohmic; the current is not proportional to the potential difference. This is because the temperature changes as increased current passes through the filament. It is ohmic for small potential differences

-
  Light-Emitting-Diode

  Current (A) vs Potential Difference (V)

  This is also non ohmic. For values of up to about 2 volts (depending on the colour of the L.E.D) the current remains at 0, so the resistance can be said to be infinite. Above 2 volts, the resistance decreases to allow current to pass through.

Experiments to Determine I-V Characteristics
- Set up a circuit diagram as shown:
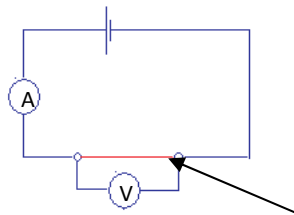
Long Thin Wire

- As to keep the current low, so that heating effect is negligible, always use a long thin wire
- Take readings from the voltmeter and ammeter
- Increase the number of cells and take readings for each added cell
- Plot a graph of current against potential difference
    - This is the I-V characteristic of the wire used

Uses and benefits of L.E.Ds
- They are being used increasingly more for light sources as a substitute to filament bulbs
- 1 can be used as the 'on' indicator on a TV; 100 can be used in a traffic light
- They emit strong sources of light
- They switch on instantly
- Very robust and versatile
- Operate on low p.ds
- Have a long working life.
- They must be connected the correct way round as they only allow current to flow in 1 direction

Resistivity
- $\rho = \frac{RA}{l}$ Where ρ is the resistivity measured in ohm meters (Ωm), A is the cross sectional area of the material measured in square metres (m^2) and l is the length of the material measured in metres (m)
- It is a constant for all materials at a set temperature

Resistivity of Metals
- Increasing temperatures increase the amount of energy metals have
- Since its volume stays the same, the increase in energy comes in the form of kinetic energy caused by the vibrations of atoms
- The conduction electrons must progress through a more turbulent mass of atoms
- This increases the resistance, and in turn the resistivity

Resistivity of Semiconductors
- The resistivity of a semiconductor decreases with temperature
- As the temperature increases, more electrons can break free of their atoms to become conduction electrons
- At the same time there are more collisions, but this number is small in comparison
- This increases the current, which decreases the resistance, and in turn the resistivity

Negative Temperature Coefficient (NTC) Thermistors
- These show a rapid change in resistance over a narrow temperature change
- Resistance decreases as the temperature of a NTC thermistor increases

Power

- The rate at which energy is transferred

Fuses as Safety Devices

- These are devices introduced into circuits to protect the wiring from excessive currents
- These high currents cause wires to get hot, damaging them, and could result in fires
- When a fuse is subjected to higher currents than what they are designed to permit, it will get too hot and melt, breaking the circuit and preventing hazardous currents

The Kilowatt-hour

- A unit of energy, not power. 1 kWh=3.6×10^6J
- It is easier for companies to measure in kilowatt-hours as typical energy consumption per month in a home in about 100 kWh, which is easier to deal with than 3.6×10^8J because to the average person, standard form means nothing, and large numbers scare people

Calculations Using the Kilowatt-hour

- Energy transferred (kWh) = power (kW) x time (h)

Voltage and Current in Series
- Voltage is shared and current is constant

Voltage and Current in Parallel
- Current is shared and voltage is constant

Kirchhoff's Second Law
- The sum of the e.m.f round a loop is equal to the sum of the p.d round the same loop
- $\sum e.m.f = \sum p.d$
- This is a consequence of the conservation of energy; since energy cannot be created or destroyed, it must be used in the circuit

Internal Resistance
- All sources of e.m.f have internal resistance
- In a battery, this is due to the chemicals inside of it, in a power supply it is due to the components and wires inside

Terminal P.d
- This is the p.d across the load (external) resistance
- Terminal p.d is the energy transferred when 1 coulomb of charge flows through the load resistance
- If there was no internal resistance the terminal p.d would be the same as the e.m.f

Resistance of a Light-Dependant-Resistor
- In the dark it has very high resistance (low light intensity)
- As it gets lighter (increasing intensity) the resistance decreases

LDRs in Potential Divider Circuits
- These are used in turning on street lamps
- When it is light, there is little resistance, therefore little p.d
- As it gets darker, the resistance increases, which increases the voltage
- When a certain voltage is reached, the lights will switch on

Thermistors in Potential Divider Circuits
- These can control the output from a heater
- When it is cold the heater needs to be turned on, this is when the thermistor has high resistance, therefore high p.d
- As it gets warmer, the resistance decreases until the p.d is below a certain point and the heater turns off
- The current is kept constant

Advantages of Using Dataloggers to Monitor Physical Change
- If a continuous record of temperature or light intensity is needed, you can connect a datalogger to the thermistor or LDR because they produce electrical outputs
- They also eliminate the chance of human error in the calculations
- Can plot accurate graphs straight away
- Very good at processing collected data

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Module 4: Waves

Progressive Longitudinal Waves
- The motion of particles are parallel to the direction of propagation
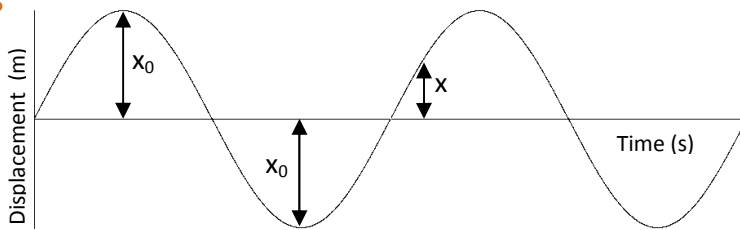
Progressive Transverse Waves

- The motion of particles is perpendicular to the direction of propagation

Displacement of a Wave (x)

- The distance from a given point on the wave to its equilibrium/rest point
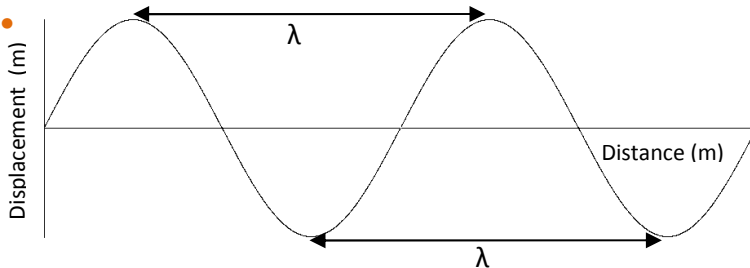
Amplitude of a Wave (x_0)

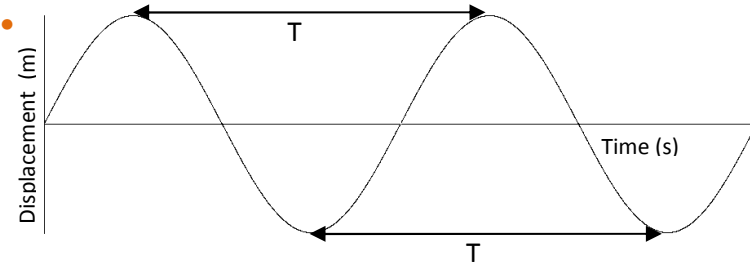- The maximum displacement from the equilibrium/rest point
-

Wavelength of a Wave (λ)

- The distance between two identical points on consecutive waves
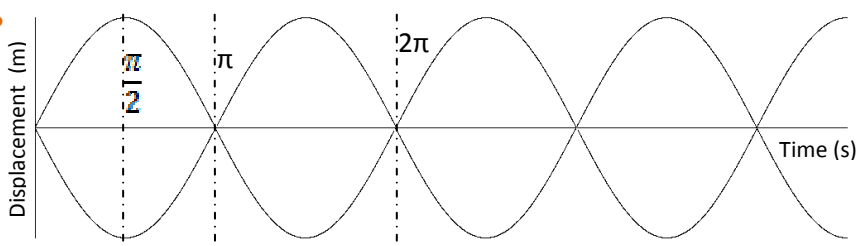-

Period of a Wave (T)

- The time taken to complete one full oscillation
-

Phase Difference (ϕ)

- The proportion of a cycle by which two waves are 'out of synch' (measured in radians)
-

- The above 2 waves are π^c out of phase. Otherwise known as antiphase

Frequency of a Wave

- The number of oscillations passing a point per second
- Calculated from $\dfrac{1}{Time\ period}$

Wave Speed

- The speed at which a wave travels
- $Speed = \dfrac{Distance}{Time}$

- When talking about waves, this becomes $Speed = \frac{Wavelength}{Time\ period}$
- But since $Frequency = \frac{1}{Time\ period}$; it becomes $Speed = Frequency \times Wavelength$
- $v = f\lambda$

How a Progressive Wave Transfers Energy
- In the case of light, energy is transferred from a source to your eye
- The wave front transfers photons to your eye
- In the case of sound energy is transferred from a source to your ear
- The wave front causes particles in air to vibrate and collide with other particles to transfer the energy

Reflection
- When a wave rebounds from a barrier, changing direction but remaining in the same medium

Refraction
- When waves change changes direction when they travel from one medium to another due to a difference in the wave speed in each medium

Diffraction
- When a wave spreads out after passing around an obstacle or gap

Electromagnetic Waves
-

Region	Wavelength (m)	Frequency (Hz)	Uses	Detection method
Gamma Rays (γ)	10^{-15}	10^{20}	Diagnosis and cancer treatment	Geiger Tube
X-rays	10^{-12}	10^{18}	CT scans, X ray photography	Photographic film
Ultraviolet	10^{-9}	10^{16}	Disco lights, tanning studios	Sunburn
Visible light	5×10^{-7}	5×10^{14}	Sight, communication	Retina of eye
Infrared	10^{-6}	10^{12}	Heaters, night vision equipment	Heating of skin
Microwaves	10^{-3}	10^{10}	Radar, mobile phones	Electronic circuits
Radio waves	1	10^{8}	Television, radio, telecommunications	Resonance in electronic circuits

- All electromagnetic waves travel at the speed of light ($3\times10^{8}ms^{-1}$)
- All posses a magnetic wave and an electrical wave interlocked at right angles to each other
- All are transverse waves
- All can travel through a vacuum
- UV-A: Wavelength 315-400nm
  - Causes tanning when skin is exposed to the sun (accounts for 99% of UV radiation)
- UV-B: Wavelength 280-315nm
  - Causes damage such as sunburn and skin cancer
- UV-C: Wavelength 100-280nm
  - Filtered out by the atmosphere and does not reach the surface of the earth

Plane Polarisation

- If a transverse wave is incident on a polariser, oscillations perpendicular to the motion are restricted to 1 plane only (they oscillate at 1 angle)
- Light is partially polarised on reflection

Malus's Law

- This describes the change in intensity of a transverse wave passing through a Polaroid analyser
- When the plane polarised light hits the analyser at an angle θ to the polarised light, the amplitude of the light is changed. It is a component of the incident amplitude. Hence $A = A_0 Cos\theta$
- From the fact that, intensity is proportional to the square of the amplitude; so the intensity *I* of the light transmitted through the analyser is given by: $I = I_0 \cos^2\theta$
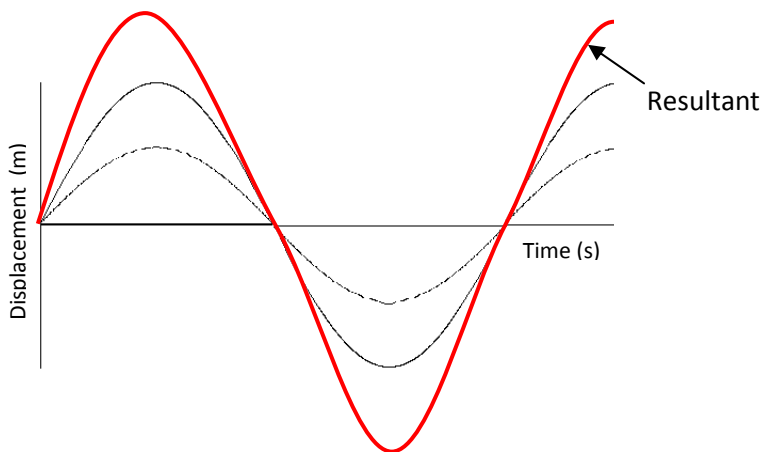
Principle of Superposition of Waves

- This states that when two or more waves of the same type exist at the same place, the resultant wave will be found by adding the displacements of each individual wave

Graphical Representation of the Principle of Superposition

- Destructive interference
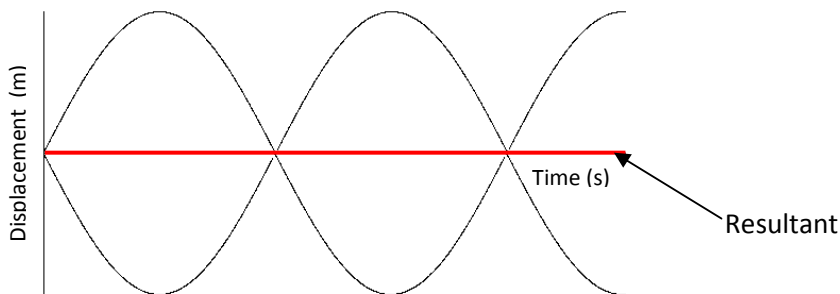
- Constructive interference

Interference

- The formation of points of cancellation and reinforcement, where 2 coherent waves pass through each other

Coherence

- Two waves with a constant phase relationship

Path Difference

- The proportion of a wavelength by which two waves are 'out of synch'

Constructive interference

- When 2 waves reinforce to give increased amplitude

- Occurs when the path difference is a whole number of wavelengths. E.g. λ, 2λ
- Occurs when the phase difference is a multiple of $2\pi^c$. E.g. 2π, 4π

Destructive interference
- When 2 waves cancel to give reduced amplitude
- Occurs when the path difference is a whole number of wavelengths. E.g. λ, 2λ
- Occurs when the phase difference is a multiple of $2\pi^c$. E.g. 2π, 4π

Experiment Demonstrating Two-Source Interference
- Connect 2 loudspeakers to the same signal generator
- As you walk in front of the loudspeakers you will hear a loud sound where the sound waves reinforce one another (constructive)
- And at other points you will hear quiet sound where waves partially cancel each other out

Young Double Slit Experiment
- Place a monochromatic light source behind a single slit, the light passes through this slit and becomes coherent
- The light then diffracts until it reaches an obstacle, in which there are 2 parallel narrow slits
- The light from these slits is coherent, as it starts from the same source and is in phase at the double slit
- From here it spreads out again by diffraction, until it reaches a screen
- The light then overlaps whilst diffracting, causing an interference pattern to form
- On the screen, bright spots will be visible
- By taking measurements of the slit spacing *a*, distance to screen *D* and the fringe (bright spot separation) *x*, you can determine the wavelength of light using the formula $\lambda = \frac{ax}{D}$

Diffraction Grating
- Young's experiment can be reproduced with multiple slits rather than just 2
- The same pattern is produced, but the fringes are much brighter and narrower, so more accurate measurements can be taken.
-
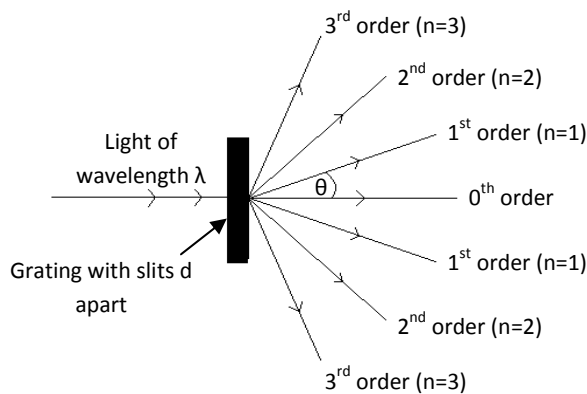
- The equation involving λ, then becomes $n\lambda = d\sin\theta$
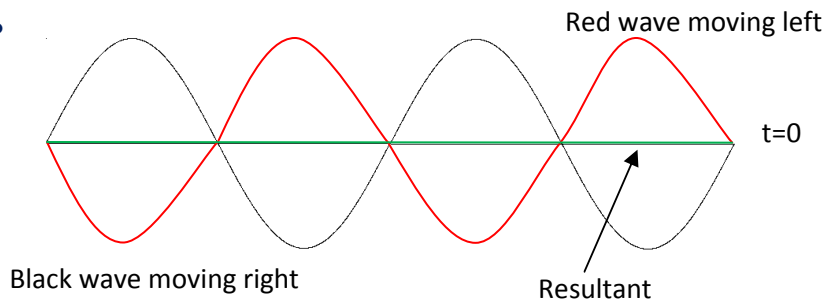- If the grating has X slits per metre, the slit spacing, $d = \frac{1}{X}$
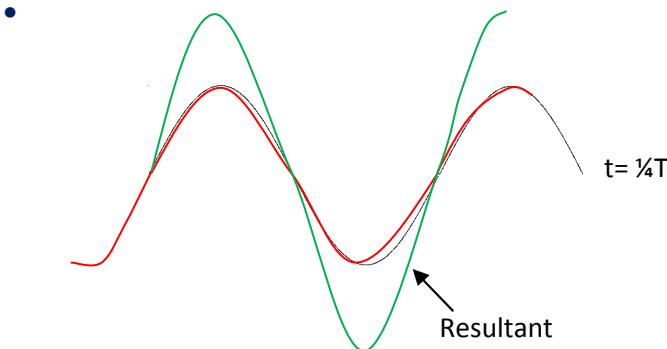
Stationary Wave
- A wave where the energy is stored, rather that transferred from place to place
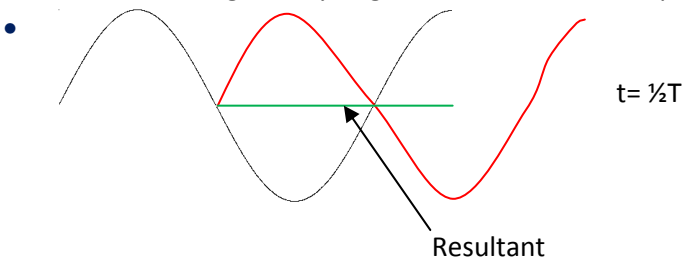
Formation of Stationary Waves
- They are formed when 2 progressive waves, of the same frequency travel in opposite directions and combine
-

Red wave moving left

t=0

Black wave moving right

Resultant

- The waves are in antiphase, the resultant is 0
-

t= ¼T

Resultant

- The black has moved ¼ of a cycle to the right and the red has moved ¼ of a cycle to the right
- The waves have moved so that their crests are in the same place
- Add these 2 together, you get a wave twice the amplitude of the 2 waves
-

t= ½T

Resultant

- This shows the wave pattern for half a cycle
- The crests line up, but since they both travel in opposite directions, only part shows the resultant zero displacement.

Nodes
- Points on stationary waves where there is no displacement of particles at any time
- Separation of adjacent nodes is $\frac{\lambda}{2}$

Antinodes
- Points on stationary waves where the displacement of particles varies by the maximum amount
- Separation of adjacent antinodes is $\frac{\lambda}{2}$

**Experiments Demonstrating Stationary Waves Using Microwaves**

- Use a microwave generator to transmit microwaves towards a metal sheet.
- The microwaves will be reflected back from the sheet along their initial path, resulting in a standing wave
- Then use a microwave detector along the stationary wave, it will register strong signals every half wavelength along the wave
- From this we can work out the wavelength, and in turn the speed of the microwaves

Demonstrating Stationary Waves Using Strings

- In a guitar, when a string is plucked, the resulting transverse wave travels up the string
- Until it hits the wood attaching the string and the guitar, the wave is then reflected back along the string, resulting in a stationary wave

Fundamental mode of vibration

- When a guitar is plucked, the simplest stationary wave that can be set up is where the length of the string is half the wavelength of the note

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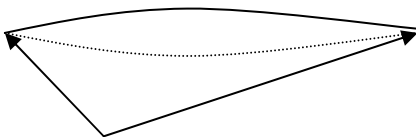
  Two points where the string is
  attached to the guitar

Harmonics

- Multiples of the fundamental frequency; which is the frequency of the fundamental mode of vibration in strings (total amount of wave visible = ½ wavelength on top and ½ on bottom)

Stationary Wave Patterns for Stretched Strings

-

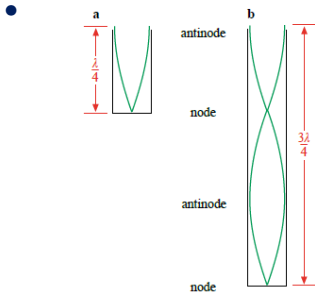|		L = length of string		wavelength	frequency
fundamental		A, N — N		$\lambda = 2L$	f_0
second harmonic		A N A, N — N		$\lambda = L$	$2f_0$
third harmonic		N A N A N A N		$\lambda = \frac{2}{3}L$	$3f_0$

- $n^{th} \ harmonic = \frac{n\lambda}{2}$

Stationary Wave Patterns for air columns in closed pipes

-

	fundamental	second harmonic	third harmonic
wavelength	$\lambda = 4L$	$\lambda = \frac{4L}{3}$	$\lambda = \frac{4L}{5}$
frequency	f_0	$3f_0$	$5f_0$

- $n^{th} \ harmonic = \frac{(2n-1)\lambda}{4}$

Stationary Wave Patterns for air columns in Open pipes

-

Determining the Speed of Sound in Air

- Place a tuning fork of known frequency f at the open end of a closed tube
- Use water to close the tube at one end
- You can find out where the maximum resonance of the wave is by gradually increasing the amount of water in the tube
- Once this is found, the distance from the water level to the top of the tube can be measured.
- This is the distance between a node and an antinode $(\frac{\lambda}{4})$
- By multiplying the distance by 4, the wavelength can be recorded. And using the equation $v = f\lambda$ the speed of sound in air can be calculated

Particulate Nature of Electromagnetic Radiation
- In 1873 it was proved that light was a wave phenomenon
- Later experiments however could not be explained using this theory
- In 1900 German Physicist Max Planck theorised that EM radiation was quantised, i.e. it behaved like a stream of particles, known as photons (quantum packets of EM energy)

Electronvolt (eV)
- 1 electronvolt is the energy change of an electron when it moves through a potential difference of 1 volt
- 1 eV = 1.6×10^{-19}J
- Since the energy of a photon is very small, the electronvolt is useful when talking about photons and electrons as it describes small amounts of energy

Planck Constant (h)
- 6.63×10^{-34}Js

Experiment to Determine the Planck Constant
- Connect an LED of known wavelength in the electrical circuit shown below
-
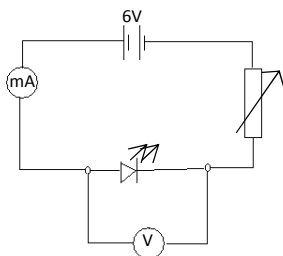
- Start off with no current flowing through the circuit, then adjust the variable resistor until a current just begins to flow
- Record the voltage (V_0) across the LED, and the wavelength of the LED
- Repeat this experiment with a number of LEDs that emit different optical wavelengths
- Plot a graph of the threshold voltage (V_0) against $\frac{1}{\lambda}$ (where λ is the wavelength of the light in metres)
- On the graph, you should get a straight line, of gradient $\frac{hc}{e}$ where h is the Planck constant, c is the speed of light and e is the elementary charge
- From this, Plank constant (h) can be calculated

The Photoelectric Effect
- If light of a high enough frequency is shined on a sheet of metal, it will emit electrons (for most metals, the frequency is in the UV range)
- Free electrons on the surface of the metal absorb energy, making them vibrate
- If an electron absorbs enough energy, the bonds holding it in to the metal break, and the electron is released
- These are called photoelectrons

Explanation of the Photoelectric Effect
- It cannot be explained by wave theory, it is evidence for the particulate nature of light
- When light hits the metal, it is bombarded by photons
- If 1 of these collides with a free electron, the electron will gain energy equal to hf

Evidence for the Wave Nature of Light
- Young's slit experiment demonstrate how light diffracts and causes interference patterns, just as sound waves do

Work Function

- The minimum energy required by a single electron to escape the metal surface

Threshold Frequency

- The minimum frequency required to release electrons from the surface of a metal

Photon – Electron Interaction

- When a photon interacts with an electron, energy is conserved
- This means the total energy of a photon is equal to the amount of energy required to release an electron from the surface of a metal + the initial kinetic energy of photoelectron
- This brings about Einstein's photoelectric equation $hf = \varphi + (\frac{1}{2}mv^2)_{max}$
- Where hf is the energy of a photon, φ is the work function energy and $(\frac{1}{2}mv^2)_{max}$ is the initial kinetic energy of the photoelectron
- The Kinetic energy is independent of the intensity because the electrons can only absorb 1 photon at a time

Photocell circuits

- The current in a photocell circuit is proportional to the intensity of the incident radiation
- For example, if you doubled the intensity of radiation incident on a photocell, the kinetic energy of the photoelectrons would stay the same
- But since there are twice as many photons in the incident radiation, twice as many electrons are released from the cell, thus doubling the current

Electron Diffraction

- Diffraction patterns are observed when accelerated electrons in a vacuum tube interact with the spaces in a graphite crystal
- This confirms de Broglie's theory that electrons show wave like properties
- Wave theory states that the spread of lines in the diffraction pattern increases if the wavelength of the wave is greater
- In electron diffraction experiments, slower electrons give widely spaced rings
- This fits in with de Broglie's equation, linking the wavelength of a particle to its velocity
- $\lambda = \frac{h}{mv}$ where h is the Planck constant, m is the mass of the particle and v is its velocity

Applications of Electron Diffraction

- by using the equation for diffraction gratings ($n\lambda = d \sin \theta$) we can work out the atomic spacing of particles in a material
- We can also determine the arrangement of atoms in crystalline structures, and the diameter of a nucleus

Ground State

- The lowest energy state that can be occupied by an electron in an atom

Discrete energy levels

- Electrons only exist at discrete energy levels
- The ground state is the first energy level. To move up a level, energy is required, so a certain amount of energy is needed. This amount of energy can only be received by a certain frequency of light, so a photon of this specific frequency is absorbed to go up a level.
- To move down a level, electrons must emit a photon, this releases energy
- This brings rise to the equation $hf = E_1 - E_2$ where E_1 is the energy of the level that the electron leaves, and E_2 is the energy of the level that the electron enters

Emission Spectra

- Hot gasses produce line emission spectra
- If a gas is heated, the electrons move to higher levels.

- As they fall back down to ground state, they emit photons, producing line emission spectra with a black background with bright lines.
- Each line corresponds to a particular wavelength of light emitted by the source.
- Since only certain photon energies can be emitted, you only get the corresponding wavelengths.

Absorption Spectra

- Cool gasses remove certain wavelengths from the continuous spectrum to produce an absorption spectrum
- At low temperatures, most of the electrons will be at ground states.
- Photons of the correct wavelengths are absorbed by the electrons to excite them to a higher energy level.
- These wavelengths are then missing from the continuous spectrum when it comes from the gas
- When looking at the sun, we do not see a full spectrum, this is because the light emitted by the sun must travel through the cooler outer layers of the sun's atmosphere, as a result certain wavelengths are filtered out