

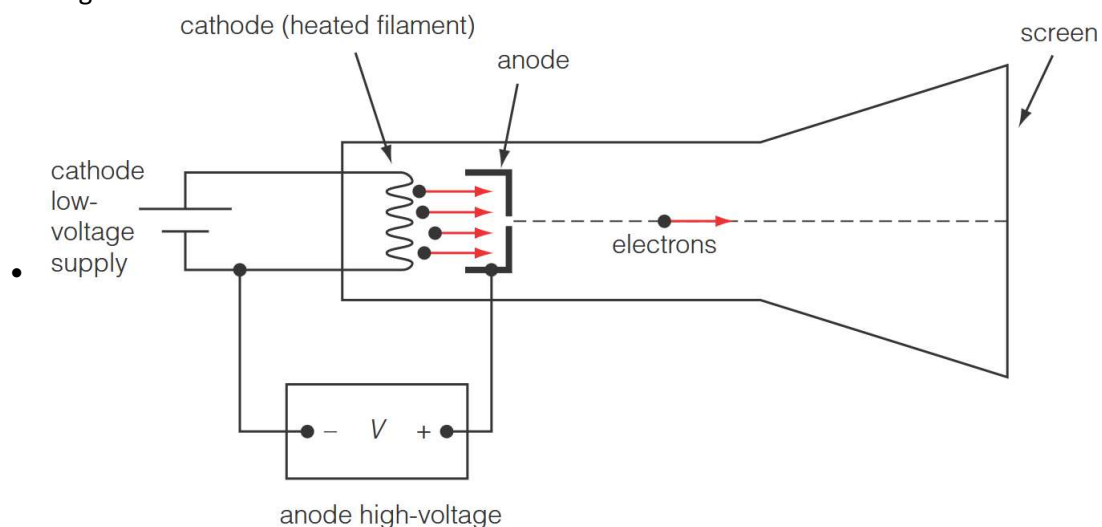
3.12.1 The discovery of the electron

3.12.1.1 Cathode rays

- Production of cathode rays in a discharge tube
 - The high pd across the discharge tube will ionise the gas atoms by pulling electrons off the gas atoms
 - The positive gas ions are accelerated towards the cathode and release more electrons when they collide with the cathode
 - The electrons are accelerated along the tube from cathode to anode and collide with gas atoms causing them to become excited
 - The excited atoms de-excite and release photons of light
 - If the gas pressure is very low
 - The electrons ejected from cathode achieve much higher speeds and travel in straight lines towards the anode → called cathode rays
 - When they strike the end of the tube they excite the atoms in the glass which then de-excites and release photons (causing the end of the tube to glow)
 - The particles were later shown to be negatively charged particles

3.12.1.2 Thermionic emission of electrons

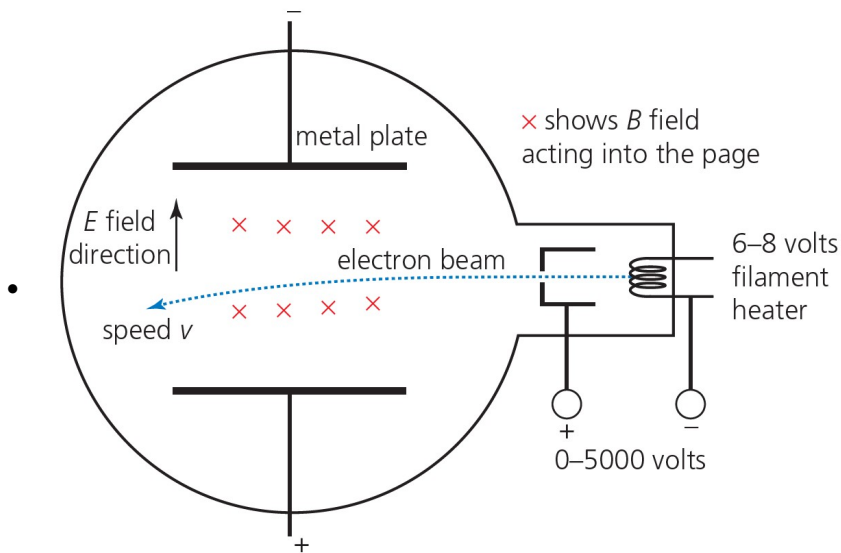
- Thermionic emission
 - The release of electrons (or charge carriers) from a heated source
 - When a metal filament is heated the conduction electrons in the metal start to move more vigorously and are able gain enough energy to leave the surface of the metal
- Electron guns



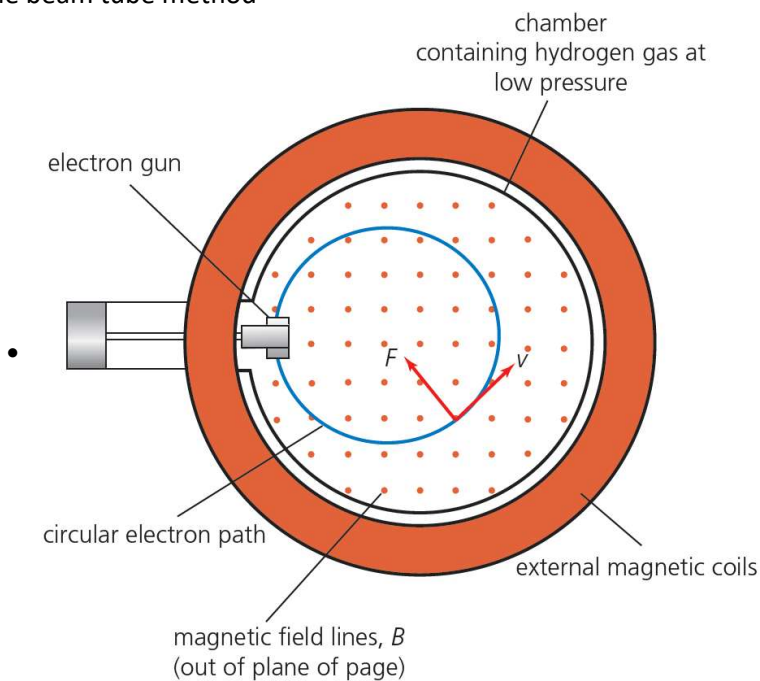
- Electrons are released by the cathode and accelerated towards the anode
- Electrons are accelerated using a potential difference (initial speed effectively zero)
- $\frac{1}{2}mv^2 = eV$
- Increasing current → higher filament temperature → more electrons have sufficient energy to leave the metal surface → more intense beam

3.12.1.3 Specific charge of the electron

- Thomson's crossed fields method for determining $\frac{e}{m_e}$



- Electrons are accelerated using an electron gun through a pd of V
- Electron beam fired into magnetic and electric fields that are perpendicular to each other and deflect the electrons in opposite directions
- Strength of the fields are adjusted until the electron beam passes through the crossed fields undeflected
- Force given to electron by electric field = Ee
- Force given to electron by magnetic field = Bev
- When electrons move in a straight line, the forces are balanced so $Ee = Bev$
- Therefore $v = \frac{E}{B}$
- Kinetic energy gained by electron: $\frac{1}{2}m_e v^2 = eV$
- Therefore $\frac{e}{m_e} = \frac{v^2}{2V} = \frac{E^2}{2VB^2}$
- Fine beam tube method

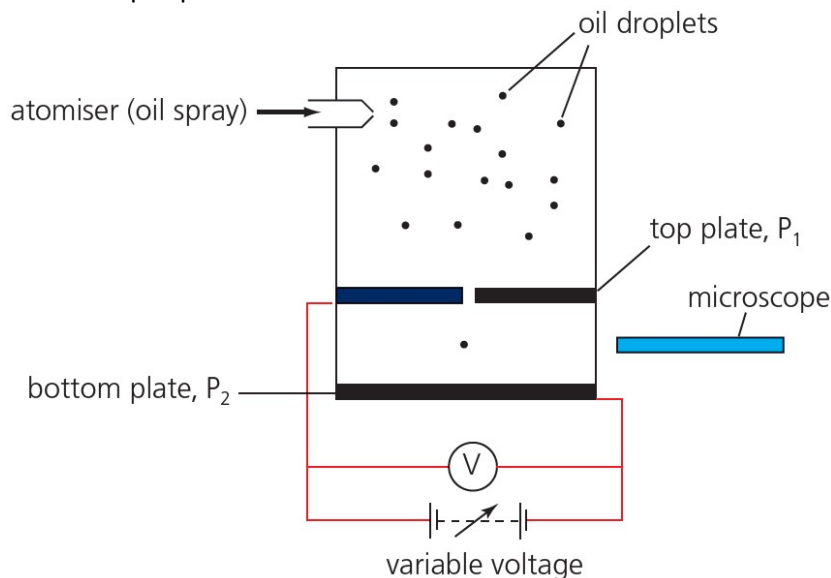


- Electrons are fired into a bulb with low pressure gas and a uniform magnetic field passing through
- The magnetic field provided centripetal force and electrons move in a circular path: $Bev = \frac{mv^2}{r}$
- Squaring both sides: $B^2 e^2 v^2 = \frac{m^2 v^4}{r^2}$
- Substituting $\frac{1}{2}mv^2 = eV$: $B^2 e^2 v^2 = \frac{mv^2 \times 2eV}{r^2}$
- Rearranging gives $\frac{e}{m} = \frac{2V}{r^2 B^2}$

- All the RHS quantities can be measured and used to calculate the specific charge
- Significance of Thomson's determination of $\frac{e}{m_e}$
 - It showed that the **specific charge was constant** whatever gas was used to produce the electrons
 - Therefore **all atoms contain electrons**
 - Thomson went on to propose the plum pudding model
- Comparison to specific charge of the hydrogen ion
 - Specific charge of electron is about $1.76 \times 10^{11} \text{ C kg}^{-1}$
 - Specific charge of a hydrogen ion (proton) is about $9.58 \times 10^7 \text{ C kg}^{-1}$
 - The specific charge of an electron is **around 1800 times larger** than that of proton

3.12.1.4 Principle of Millikan's determination of the electronic charge, e

- Stoke's Law
 - For a spherical object moving, the viscous force $F = 6\pi\eta r v$
 - η = viscosity of the fluid
 - r = radius of the object
 - v = terminal velocity of the object
- Millikan's oil drop experiment

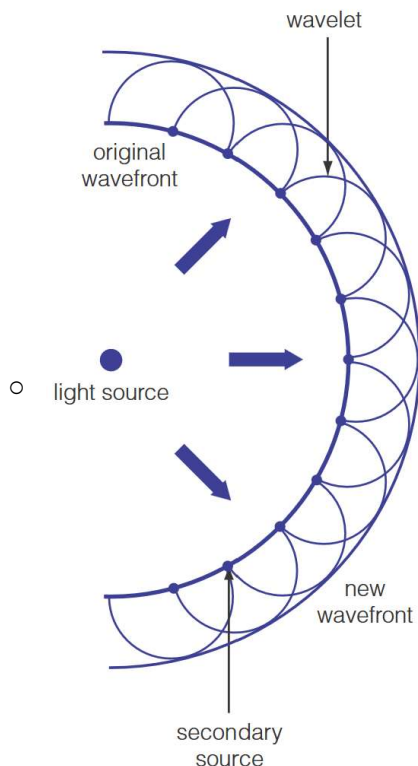


- Force and weight are balanced when the oil drops are stationary: $EQ = mg$
- Since $E = \frac{V}{d}$, $\frac{QV}{d} = mg$, so mass of the droplet is needed to determine the charge
- Using volume of sphere: $m = \frac{4}{3}\pi r^3 \rho$ so only the radius is needed
- Radius is determined by observing the motion of the same droplet when the electric field is switched off
- Only weight and resistive forces acting on the oil drop when the field is switched off \rightarrow find terminal speed
- At terminal velocity v : $F = mg$
- Using Stoke's Law: $mg = 6\pi\eta r v \rightarrow \frac{4}{3}\pi r^3 \rho g = 6\pi\eta r v \rightarrow r = \sqrt{\frac{9\eta v}{2\rho g}}$
- With η and ρ known: r can be found and hence Q
- Significance of Millikan's results
 - The charge of all the oil droplets **was an integer multiple of $1.6 \times 10^{-19} \text{ C}$**
 - This is the smallest possible magnitude of charge \rightarrow magnitude of charge carried by an electron

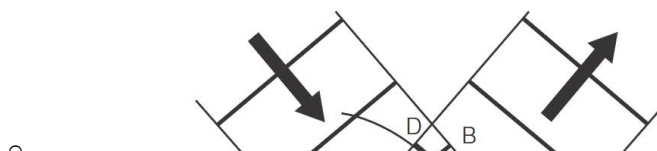
3.12.2 Wave-particle duality

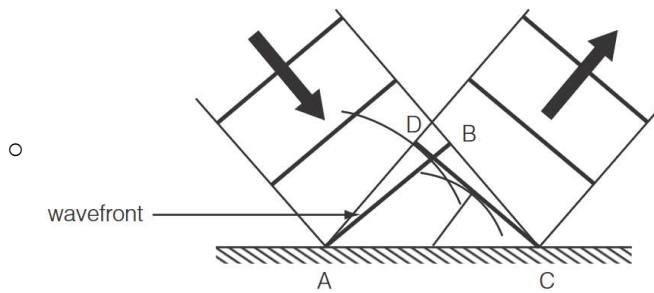
3.12.2.1 Newton's corpuscular theory of light

- Newton's corpuscular theory of light
 - **Light was formed of tiny particles called corpuscles**
 - Reflection explanation
 - The corpuscles collide with the surface
 - A repulsive force pushes them back
 - Their component of velocity perpendicular to the surface reverses direction
 - Their component of velocity parallel to the surface stays the same
 - Refraction explanation
 - As the corpuscles approach a denser medium short-range forces of attraction causes their component of velocity perpendicular to the surface to increase
 - The parallel component of velocity stays the same
 - Light will bend towards the normal and **travel faster in denser mediums (false)**
 - **Diffraction of light cannot be explained** with Newton's theory (it was not observed at the time)
- Huygens' theory of light
 - **Light behave as (longitudinal) waves**
 - Every point on a wavefront is a point source to secondary wavelets which spread out to form the next wavefront

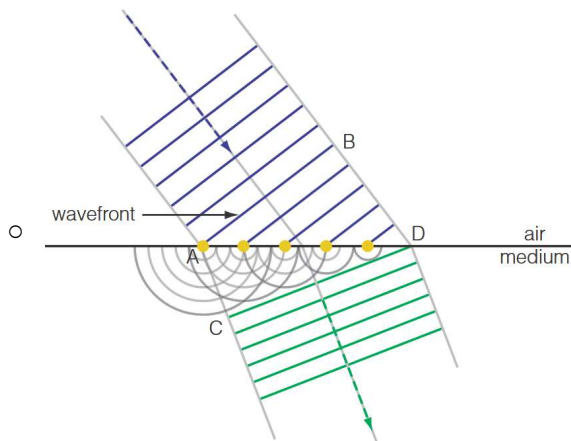


- Reflection explanation
 - The whole wavefront will not reach the surface at once unless travelling perpendicular to the surface which
 - The point at which the wavefront is reflected acts as a secondary source and new wavelets are formed
 - Wavelets spread away from the source once they react it and rejoin with others to reform the reflected wavefront





- Refraction
 - **Assumed that light travels slower in a denser medium**
 - As it entered a more optically dense medium it would slow down and therefore bend towards the normal



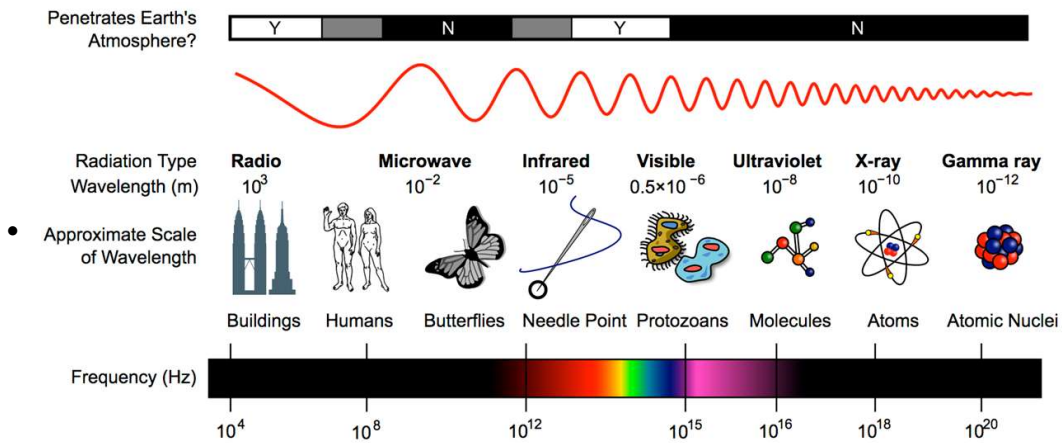
- Why Newton's theory was preferred
 - Newton had a much stronger scientific reputation than Huygens
 - It was not possible to measure the speed of light in air / transparent substance at the time so no experimental evidence to determine whether light travels faster in air or a transparent substance
 - Diffraction had not yet been observed so there was no evidence to disprove Newton's theory

3.12.2.2 Significance of Young's double slit experiment

- Young's double slit experiment
 - Coherent light is shown through 2 slits so that it diffracts
 - Each slit acts as a coherent light source
 - Light fringes formed when the path difference is an integer number of wavelengths → meet in phase and interfere constructively
 - Dark fringes formed when the path difference is a whole number and a half of wavelengths → meet completely out of phase and interfere destructively
- Significance of its result
 - According to Newton's theory the 2 slits would just produce 2 bright fringes corresponding to themselves instead of an interference pattern (particles don't diffract)
 - According to Huygen's wave theory an interference pattern would be produced
 - **Diffraction and interference are wave properties → light must be a wave**
 - Young accepted Huygen's idea that there must exist an ether to act as a medium to carry the light waves
 - Huygen's theory widely wasn't widely accepted until the speed of light was measured
 - It was discovered that light travels slower in water than air as contrary to Newton's predictions
 - The acceptance was delayed due to Newton's historical prestige so that the scientists expected Newton to be correct

3.12.2.3 Electromagnetic waves

- The electromagnetic spectrum

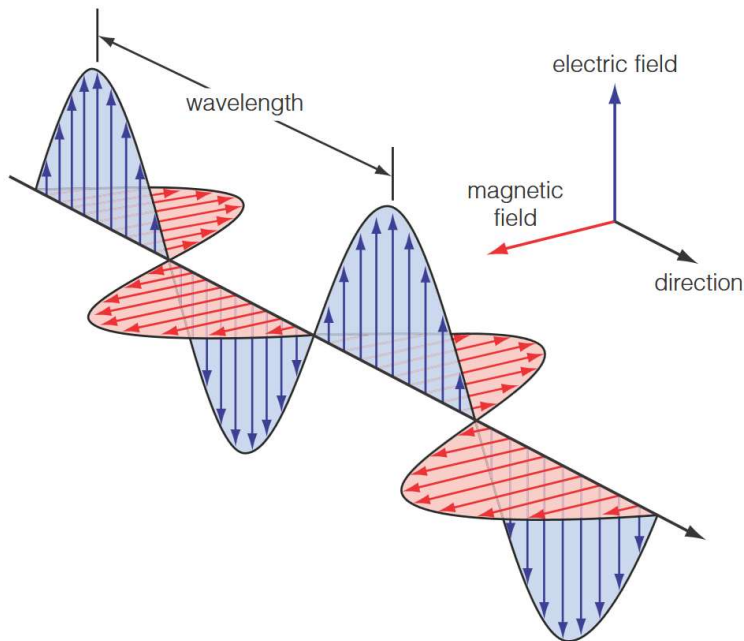


• Sources of different electromagnetic waves

Region	Wavelength range / m	Origin
Radio waves	10^{-1} to 10^6	Oscillations in electric fields
Microwaves	10^{-3} to 10^{-1}	Molecular interactions
Infrared (IR)	10^{-7} to 10^{-3}	
Visible	4×10^{-7} to 7×10^{-7} (400–700 nm)	
Ultraviolet (UV)	10^{-9} to 10^{-7}	Energy transitions within atoms
X-rays	10^{-13} to 10^{-8}	
Gamma rays	10^{-16} to 10^{-10}	Nuclear de-excitation

• Maxwell's theory of electromagnetic waves

- An electromagnetic wave can exist when a changing electric and magnetic field each continuously induce the other
- It can travel through space at a transverse wave with the electric and magnetic field components oscillating in phase + at right angles to each other and to the direction of travel



- Maxwell's formula for the speed of electromagnetic waves in vacuum

- $c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$

- μ_0 = permeability of free space

- Relates the magnetic flux density of a magnetic field to the electric current that creates it

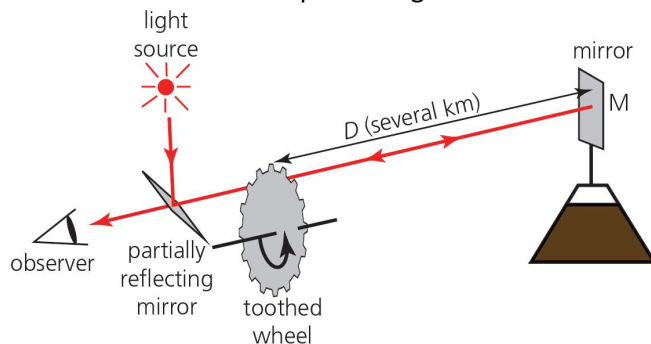
- Unit H = henry, $1 \text{ H} = 1 \text{ VsA}^{-1}$

- ϵ_0 = permittivity of free space

- Relates the electric field strength to the charge that creates it

- Unit F = farad, $1 \text{ F} = 1 \text{ C V}^{-1}$

- Fizeau's determination of the speed of light

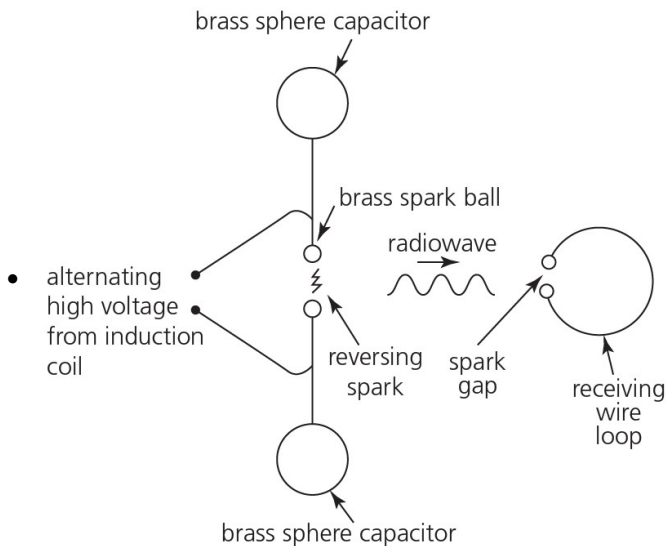


- Shine light beam at a partially reflecting mirror
- Light reflected towards the distant mirror several kilometres (distance of D) away
- Light passes between the teeth of a rotating toothed wheel with N teeth and N gaps of equal widths to the mirror
- Mirror reflects the light and light travels back through the teeth of the wheels again
- The minimum frequency at which light cannot be seen is recorded
- At this frequency the time it takes to through the width of one tooth / gap is the same as the time it takes for the light to travel from the wheel to the mirror and back

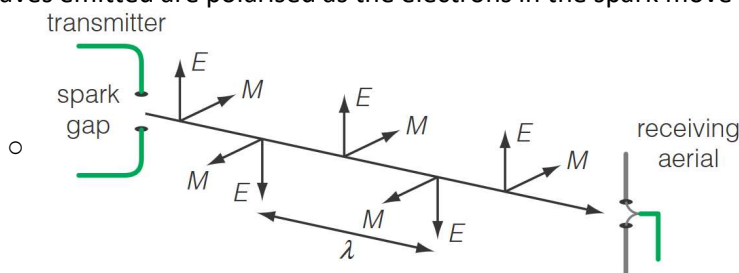
- $t = \frac{T}{2N} = \frac{1}{2Nf} = \frac{2D}{c}$

- $\therefore c = \frac{2D}{(2Nf)^{-1}} = 4DNf$

- Hertz's discovery of radio waves



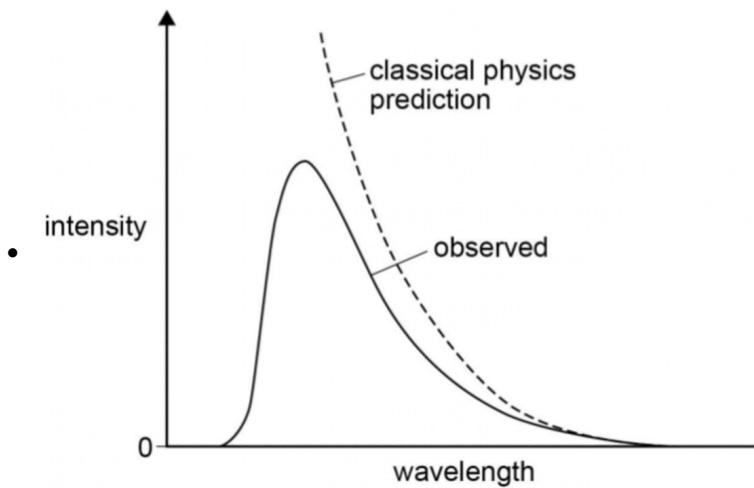
- Electromagnetic waves could be produced by a spark created by an electrical discharge
- Radio waves are produced when high voltage sparks jump across a gap of air
- The radio waves can be detected with a loop of wire with a gap
 - This will detect the waves' alternating magnetic field as the field will enter the loop causing a change in the magnetic flux
 - Emf is induced in the wire loop → current induced
 - Sparks are created between the brass spheres of the detector
- Waves emitted are polarised as the electrons in the spark move in one plane



- The signal strength gradually reduces from a maximum value when the receiving gap is in line with the spark gap to zero when it is perpendicular to the gap
- Radio waves could be reflected by a metal sheet → stationary waves are created
 - Wavelength can be found by measuring the distance between adjacent nodes (half a wavelength)
 - Speed calculated by Hertz ($c = f\lambda$) was found to be the same as the one predicted by Maxwell → radio waves are EM waves
- Radio waves pass through insulators / focused by a concave reflector

3.12.2.4 The discovery of photoelectricity

- Black body
 - An object that absorbs or emits **all wavelengths of electromagnetic radiation** falling on the object
 - It does not reflect any wavelengths
 - The emission spectrum (how much energy is emitted at each wavelength) depends only on the absolute temperature (T) of the object
- Black body experimental results
 - The intensity increases with increasing temperature
 - The total power of the emitted radiation (area under the curve) emitted increases with increasing temperature
 - The peak wavelength decreases with increasing temperature
- Ultraviolet catastrophe



- Prediction with wave theory
 - As the wavelength of the radiation decreases, the intensity of the radiation would increase
 - Leads to a prediction of an infinite amount of UV radiation being emitted
 - **Not supported by experimental evidence**
- Could be resolved by using Planck's interpretation of electromagnetic waves
 - Energy of electromagnetic waves are **quantised**
 - The size of a quantum of electromagnetic energy is given by $E = hf$
- Wave theory's problem with photoelectricity
 - There is no photoemission below the threshold frequency even with bright light
 - Wave theory would allow gradual accumulation of energy to cause emission
 - Any frequency of light should be able to cause electron emission
 - Electrons are emitted with no noticeable decay
 - In wave theory time would elapse while an electron gains sufficient energy to leave the surface
 - Intensity of the light does not affect the KE of the emitted electrons
 - High intensity waves would be expected to give higher KE to an electron
- Einstein's explanation of photoelectricity with photons
 - When light is incident on a metal surface an electron at the surface absorbs a **single photon** from the incident light and gains energy equal to hf
 - All of the photon's energy is transferred to the electron
 - All electrons receive the same amount of energy
 - The energy is transferred to the electron immediately when they interact → photoelectrons emitted immediately
 - An electron can leave the metal surface if the energy gained > the work function of the metal
 - Electrons deeper in the metal need more energy as they lose energy via collisions
 - Excess energy gained becomes KE of the photoelectron
- Significance of Einstein's explanation
 - Established the wave-particle duality of light
 - Proved Planck's 'quanta' model of electromagnetic radiation

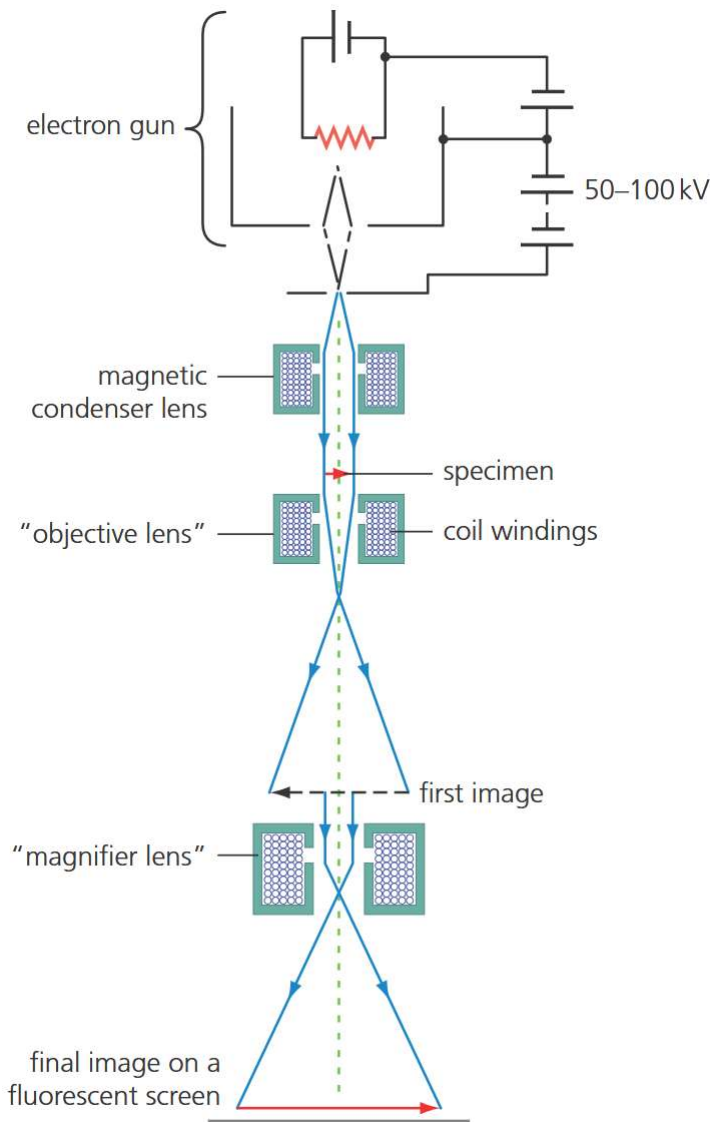
3.12.2.5 Wave-particle duality

- De Broglie wavelength
 - $\lambda = \frac{h}{p} = \frac{h}{mv}$
- Electron diffraction
 - Provided experimental evidence for de Broglie's prediction of the existence of matter waves
 - If electrons were particles there will simply be a bright spot on the screen as electrons are diffracted randomly
 - Diffraction is a wave property
 - Electrons are fired towards a crystal lattice with an electron gun
 - We can control the de Broglie wavelength of the electrons emitted by adjusting the pd across the anode

- $\frac{1}{2}mv^2 = eV$
- $m^2v^2 = 2meV$
- $mv = \sqrt{2meV}$
- $\lambda = \frac{h}{\sqrt{2meV}}$
- Higher pd = shorter wavelength
- The electrons interacted with the small gaps between atoms and formed a diffraction pattern on a fluorescent screen behind the crystal
- As pd increase the de Broglie wavelength of electron decreases so the fringe spacing decreases (and vice versa)
- This follows wave theory which states that fringe spacing increases as wavelength increases

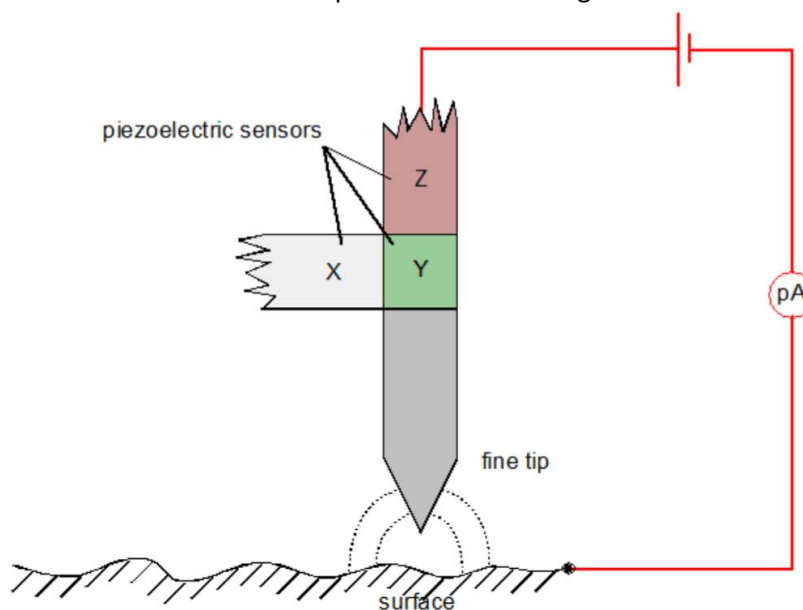
3.12.2.6 Electron microscopes

- Voltage used
 - The de Broglie wavelength of the electron should be of the order of the size of the atom to have enough resolving power
 - About 0.1 nm = 10^{-10} m
 - $\lambda = \frac{h}{\sqrt{2meV}} \rightarrow V = \frac{h^2}{2me\lambda^2}$
- Transmission electron microscope (TEM)



- The sample must be **extremely thin** so the electrons do not slow down and wavelength do not change
- Electrons pass through 3 lenses

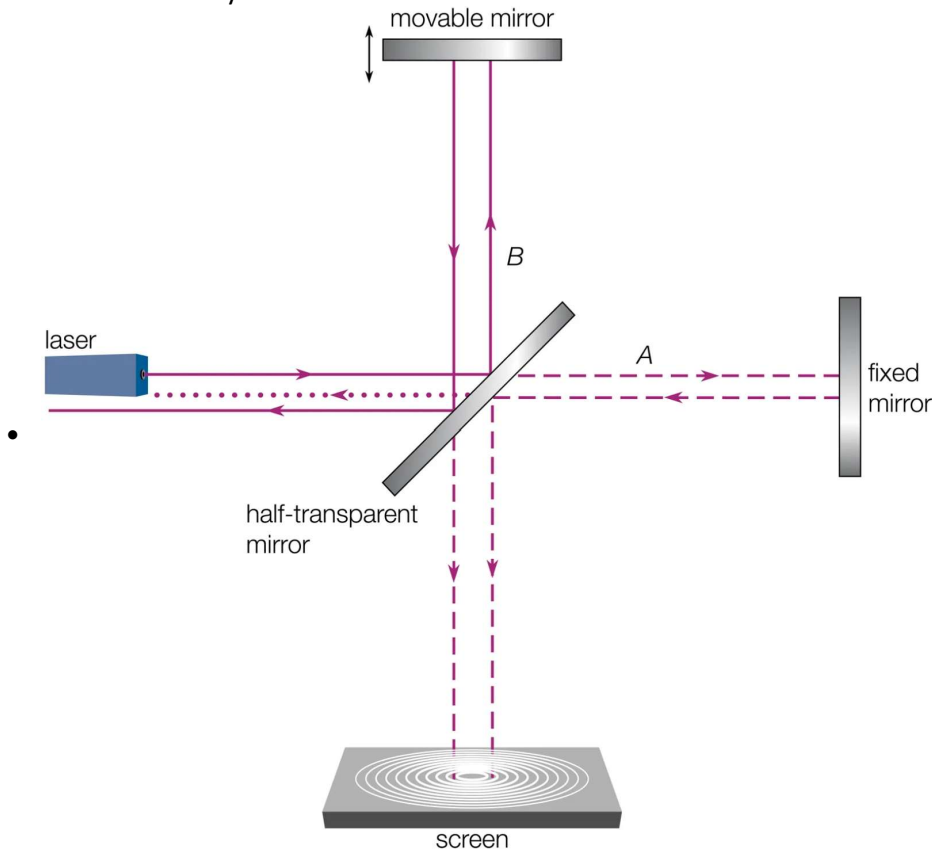
- Condenser lens deflects: the electrons so that they form a wide parallel beam
- Objective lens: form an image of the sample above it
- Projector lens: magnify the image made by the objective lens and project it onto the fluorescent screen
- Higher accelerating voltage = lower wavelength = higher resolving power
- Limited resolving power
 - Sample thickness slows down the electron so wavelength increase and reduces the resolving power
 - Electrons travel at a range of speeds since some lose KE while leaving the source metal so they have different wavelengths and different diffraction patterns causing blurred image
- Scanning tunnelling microscope (STM)
 - Uses quantum tunnelling of electrons to form an image of the object surface
 - Quantum tunnelling arises due to the wave nature of electrons
 - If the barrier that the electrons are trying to cross (physical or potential) is small enough then the electrons can move across it like light waves
 - Smaller gap = increased likelihood of quantum tunnelling occurring
 - Has a very fine tipped probe which moves across the surface and stays at a constant potential
 - Electrons can only travel in one direction
 - As the probe moves across the surface the size of gap between probe and surface varies and the tunnelling current changes
 - Increases if the gap becomes narrower
 - Decreases if the gap becomes larger
 - Two operation modes
 - Constant height mode: the probe is kept at a constant height and the current is recorded and used to image the object surface
 - Constant current mode: the current is kept constant by adjusting the probe's height and the movement of the probe is used to image the surface



3.12.3 Special relativity

3.12.3.1 The Michelson-Morley experiment

- The ether
 - It was believed that light travels in medium call ether
 - The speed of light in ether is constant
 - Sun was thought of being approximately at rest reloative to the ether
 - The Earth was believed to be moving relative to the ether
 - Speed of light depends on the Earth's velocity relative to the ether and its direction to Earth's velocity
- The Michelson-Morley interferometer



- One direction is set to be moving parallel to Earth's motion and the other side is perpendicular to Earth's motion
- The same distance is travelled by light deflected to both directions before reaching the screen
- An interference pattern is created on the screen
- Expected result
 - The time taken for the light travel in the 2 tracks should be different to each other as their speed is different
 - Light moving parallel to Earth's motion will take longer to travel
 - Light moving perpendicular to Earth's motion has its speed unaffected
 - Expected to observe a small but observable shift of the interference fringe pattern (phase difference)
- Observed result
 - No fringe shifts were observed (even when rotating the apparatus)
 - Conclusion: **the speed of light was the same whether the observer was moving relative to the source or not**
 - The experiment showed that there is no absolute motion (which the ether could have acted as)
 - Ether did not exist so light travels without the need for a material medium
 - The Earth was dragging the ether with it (assuming ether existed although it doesn't)

3.12.3.2 Einstein's theory of special relativity

- Inertial frame of reference
 - A reference frame in which Newton's Laws hold
 - Moves at a constant velocity
- Einstein's postulates of special relativity
 - Physical laws have the same form in all inertial frames
 - The speed of light in free space is invariant

3.12.3.3 Time dilation

- Muon decay experiment
 - Using a Geiger counter to detect cosmic muons at an altitude at 2km and at sea level
 - Half-life of muons = 1.5 μs \rightarrow most should decay before reaching sea level as it takes 6.7 μs to travel 2km at muon's speed
 - Reality: 80% reached sea level
- Lorentz factor
 - $$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$
- Time dilation
 - $$t = \gamma t_0 = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$
 - t is time interval measured by reference frame **moving** relative to object being observed
 - t_0 is time interval measured by reference frame **stationary** relative to object being observed (proper time)
- Muon g-2 experiment explanation with time dilation
 - The time measured by muon (stationary relative to muon) is much shorter than time measured by human (moving relative to muon)
 - Much shorter time to decay than as measured by human

3.12.3.4 Length contraction

- Length contraction
 - A ruler / pen moving in the same direction as its length **appears shorter than when it is stationary**
 - $$l = \frac{l_0}{\gamma} = l_0 \sqrt{1 - \frac{v^2}{c^2}}$$
 - l is length measured by a reference frame **moving** relative to the object
 - l_0 is length measured by a reference frame **stationary** relative to the object (proper length)
- Muon g-2 experiment explanation with length contraction
 - The length from atmosphere to ground measured by muon (moving relative to Earth) is much shorter than the distance measured by human (stationary relative to Earth)
 - Much shorter time is needed to travel the distance

3.12.3.5 Mass and energy

- Relativistic mass
 - $$m = \gamma m_0 = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$
 - m_0 = proper mass observed in a reference frame stationary relative to the object
 - m = larger mass observed in a reference frame moving relative to the object
- Relativistic kinetic energy
 - $E = mc^2 = \gamma m_0 c^2$
 - When at rest: $E_0 = m_0 c^2$
 - The difference between the 2 energies is the KE of the object

