Light?

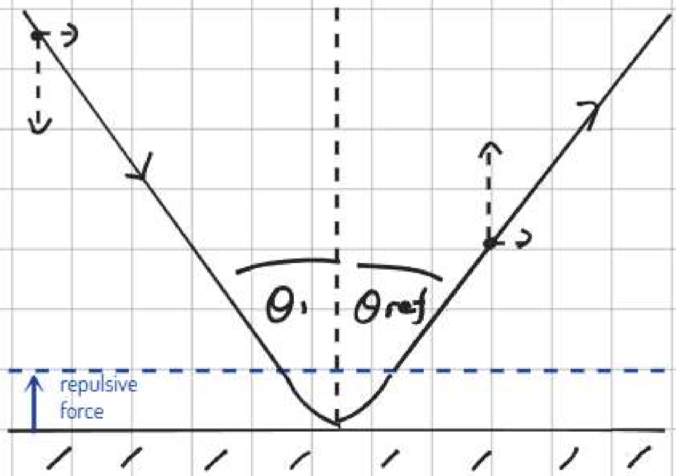
27th March 2026

The end of the 17th Century saw conflicting views on the nature of light.

Newton's Corpuscular Theory

Newton proposed that light behaves as a stream of particles.
These particles travel in straight lines unless experiencing a force.

Reflection



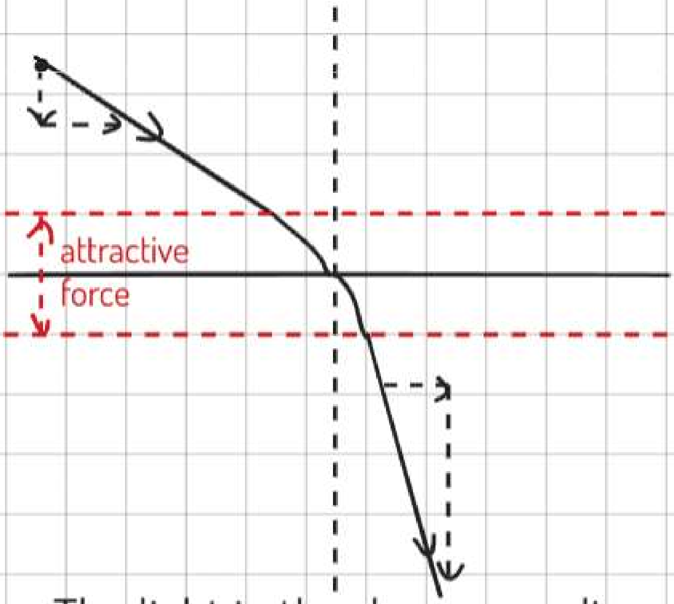
When a corpuscle of light approaches a reflective surface it experiences REPULSION.

The horizontal component stays CONSTANT.

The vertical component decreases past zero to its original magnitude in the opposing direction.

The final speed of light is the same before and after hence $\theta_i = \theta_{ref}$

Refraction



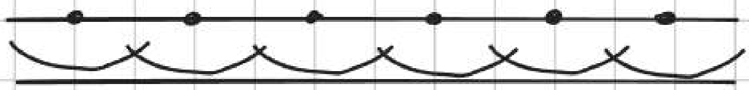
As light approaches a transparent medium it accelerates due to an ATTRACTIVE force. It is directed towards the denser medium.

The vertical component INCREASES whilst the horizontal component remains CONSTANT.

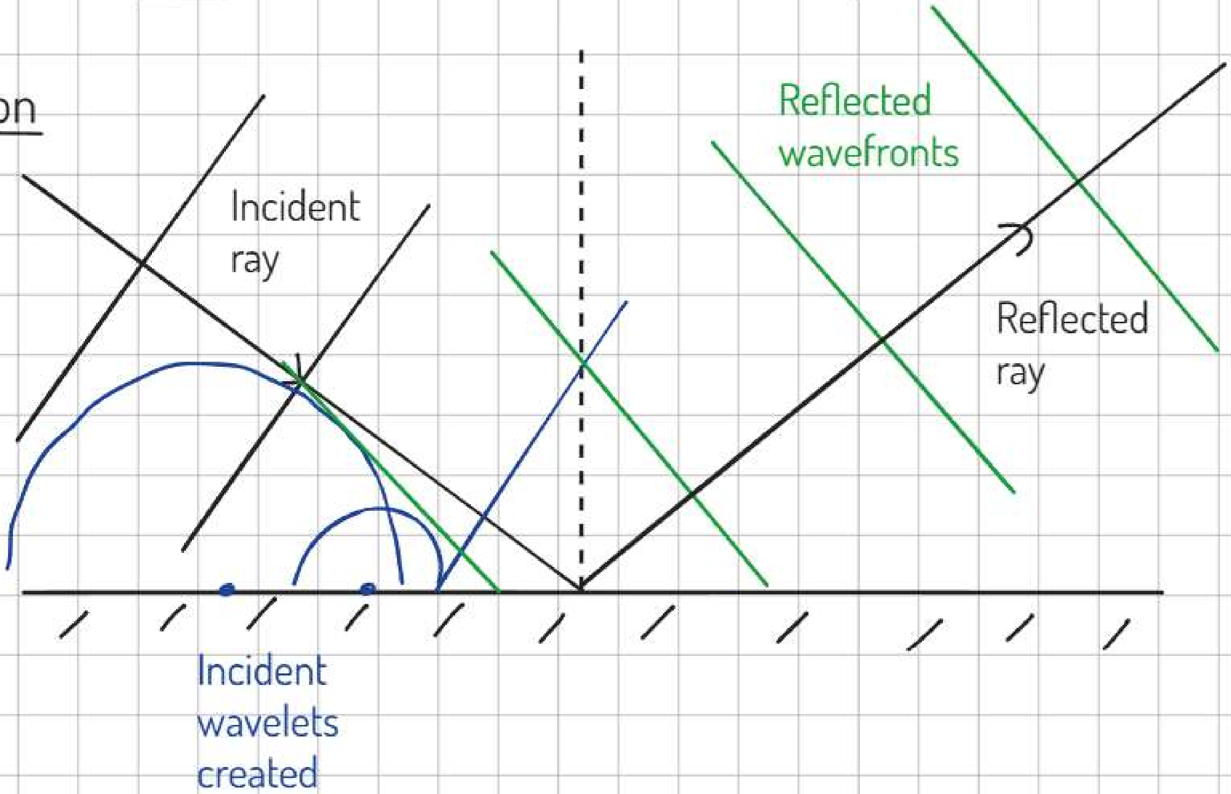
The light in the denser medium moves FASTER.

Huygen's Wave Theory

Huygen's proposed that each point along a wavefront of light acted as a secondary source of waves, spreading out in circles. They then combine through a process of superposition to form the next wavefront.

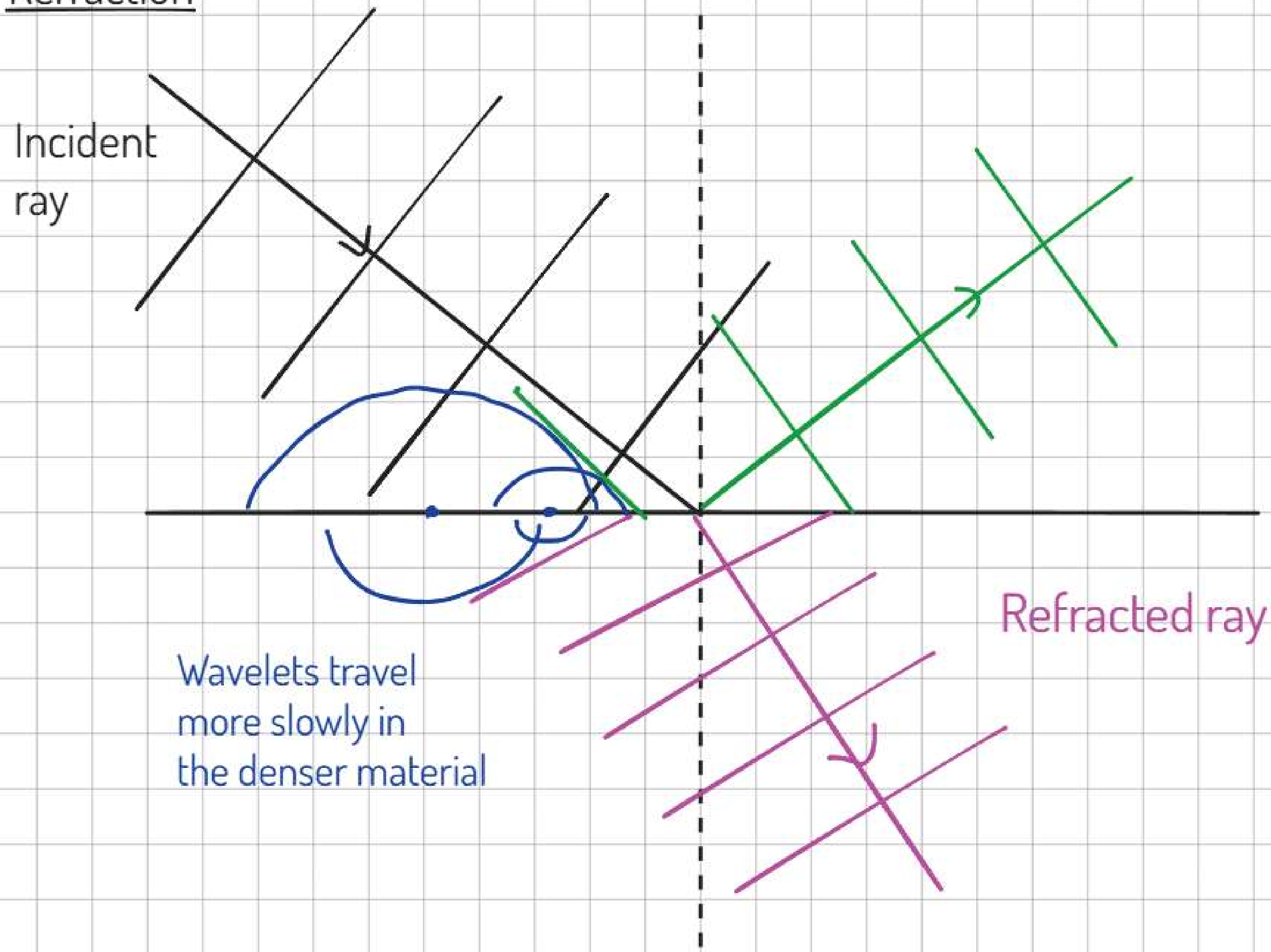


Reflection



Incoming wavefronts hit the mirrored surface and create secondary wavelets. The secondary wavelets spread out and interfere to form the reflected wavefronts. These produce further wavelets which produce a series of wavefronts propagating away from the mirror.

Refraction



Wavelets in the denser material travel MORE SLOWLY in the denser medium.

The Ether

Huygens invented a medium called the LUMINIFEROUS ETHER so that light could travel from the Sun and stars to Earth.

Dominance of Newton

His reputation played a big part in this...

Shadows

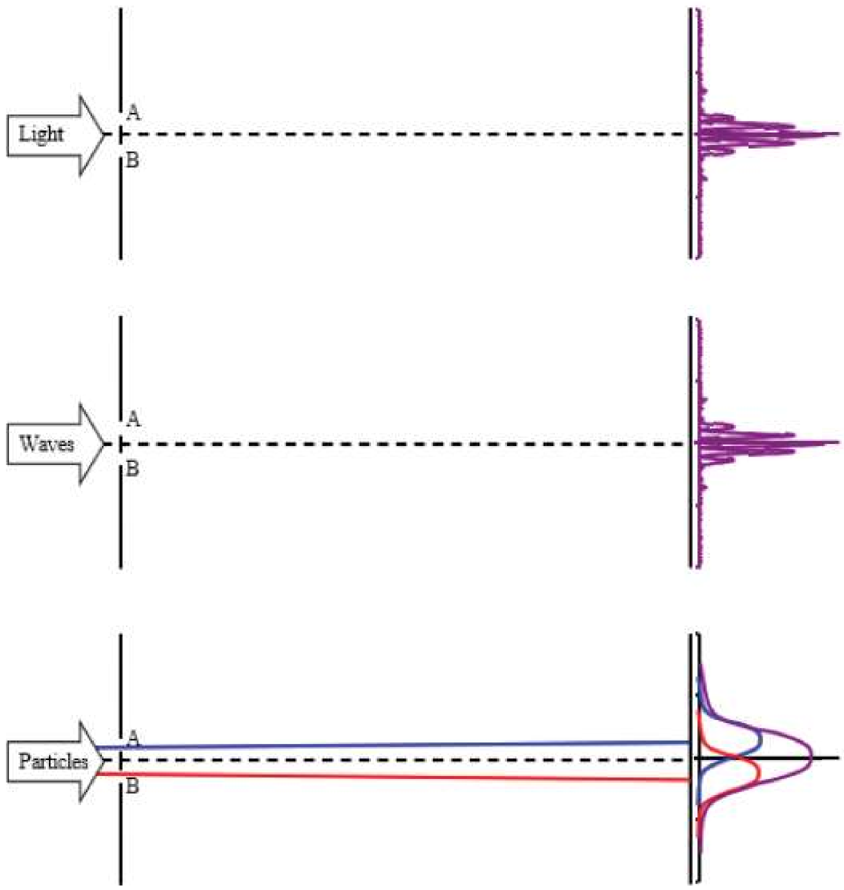
When a large opaque object is placed in the path of light it forms a shadow.
In wave theory, the light should bend around the object.
Particles should travel in a straight line casting clean shadows.

The speed of light

Was unknown.

1807

Young's double slit experiment.



This led to observation of diffraction and superposition.

All supporting Huygen's wave theory.

Later Fresnel produced a mathematical treatment of diffraction showed that it was only apparent when wavelength was comparable to order of magnitude of the object. (hence shadows)

In 1850 Foucalt measured the speed of water and found it was SLOWER than in air.

LIGHT IS A WAVE

EM Waves

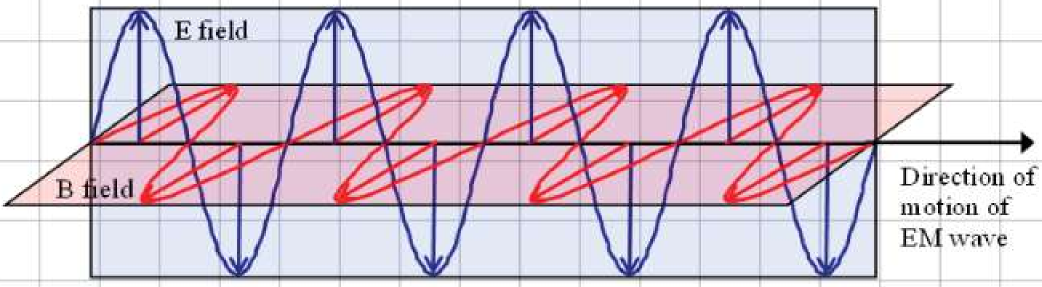
31st March 2026

Electric fields are:
- associated with potential differences.
- exert forces on charged particles
- create a current when applied to a wire
- can create a magnetic field

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)$$

A changing magnetic field in a loop of wire can create changing potential difference. Faraday discovered that an alternating E field can create an alternating B field.

Even in free space an alternating electric field could create an alternating magnetic field and vice versa. The alternating fields would be IN PHASE, could be POLARISED depending on direction of E field and TRANSVERSE.



He proposed a broad spectrum of frequencies and wavelengths and calculated their speed:

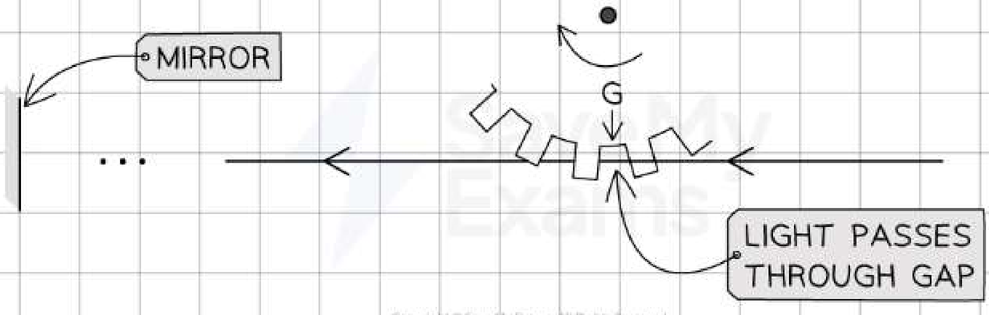
$$C = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

μ_0 permeability of free space $4\pi \times 10^{-7}$ Hm^{-1}

ε_0 permittivity of free space 8.85×10^{-12} Fm^{-1}

$$c = 2.9979 \times 10^{8} \, ms^{-1}$$

Fizeau



Fizeau passed a beam of light through a gap between the teeth of cog wheel, which then passed to a mirror ~ 9km away.
The cog rotated just enough to block the beam on its return.

Using the number of gaps and frequency of rotation he could calculate time to the reflector and back.

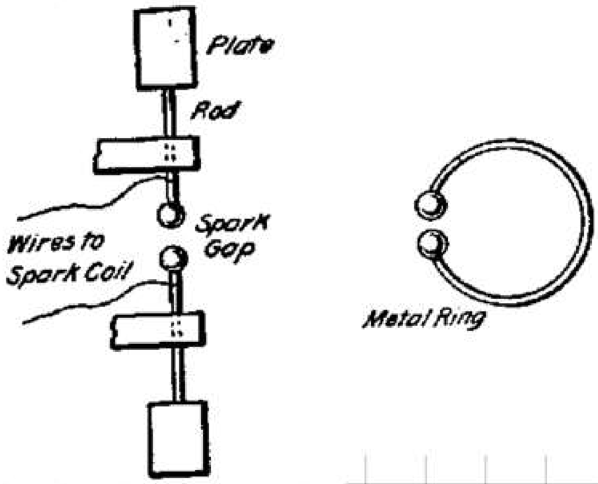
Suppose a gear with N teeth and time period T, a distance D from the reflector.

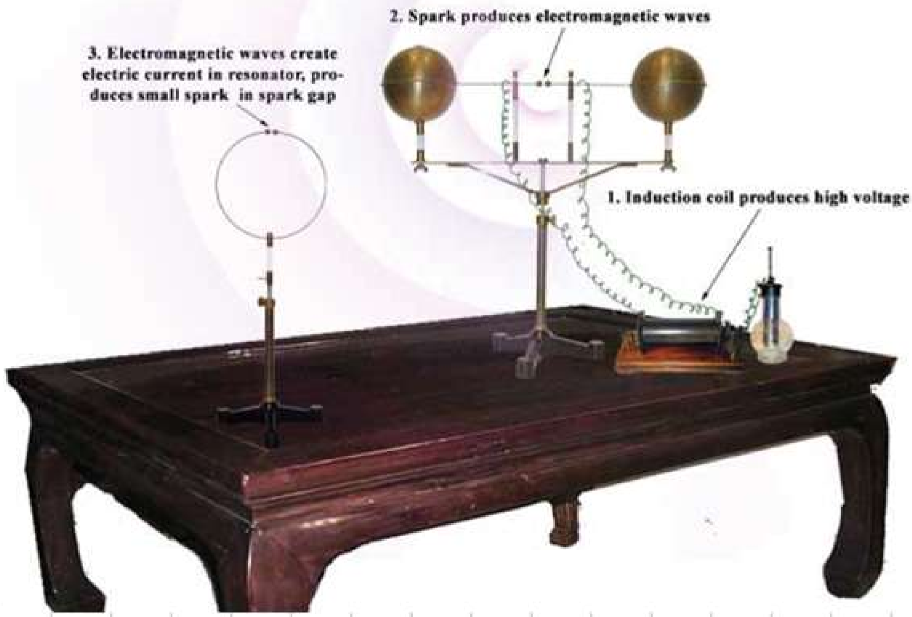
$$t = \frac{T}{2N} \qquad c = \frac{2D}{t}$$

$$c = \frac{2D}{(T/2N)} = \frac{4DN}{T}$$

$$\boxed{c = 4DNf}$$

Hertz



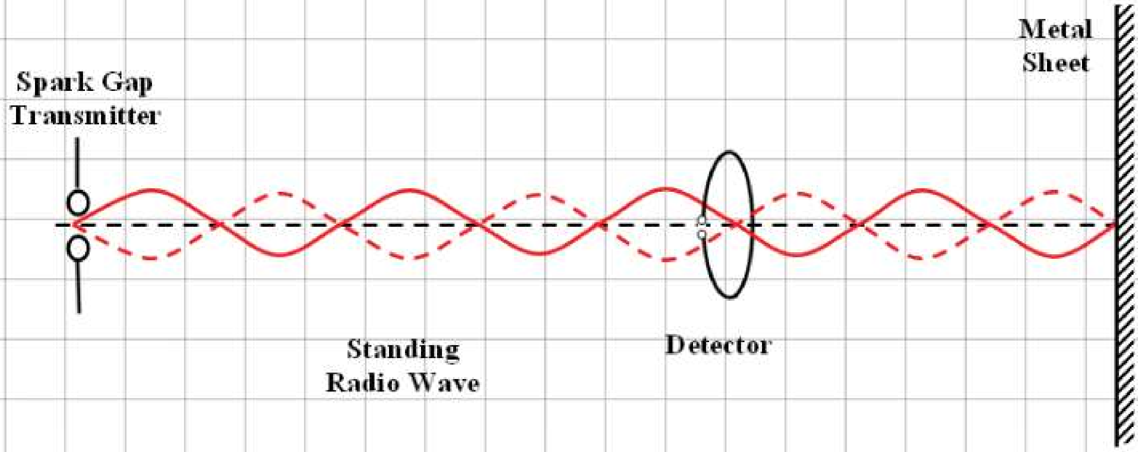


The induction coil produced pulses of large p.d. which charged the metal plates. When the p.d. was high enough a spark would cross the gap and discharge the plates. During this process the plates underwent a damped oscillation.

The alternating magnetic field around the emitted radio waves produced a varying electric field round the loop of wire. This led to a spark jumping across the gap in the metal ring.

He was able to show that the detections were polarisable waves.

Speed of Radio Waves



When the detector was placed at an anti-node spark are observed. Hertz assumed that the 'strongest' sparks corresponded to the natural frequency of the detector, so there was resonance. So he recorded the natural frequency.

When at a node there we no sparks, so he was able to record a distance 'd', between node and anti-node.

$$\lambda = 2d$$

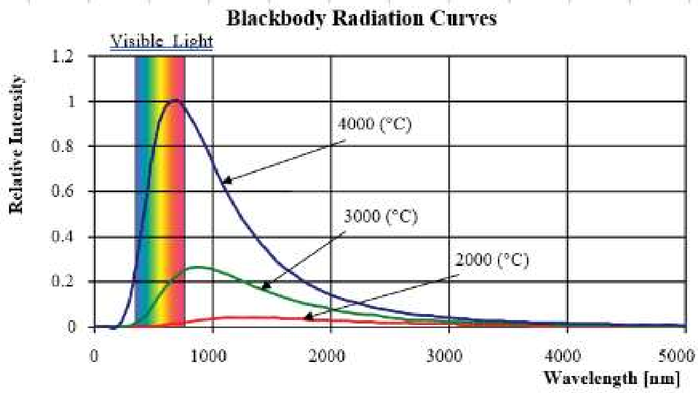
By comparing his speed to Maxwell's
he concluded that radio waves are electromagnetic.

Light as a particle

08/02/24

A blackbody is a perfect absorber and emitter of EM radiation.

In classical wave theory the relative intensity tends to infinity around the UV region of the spectrum.



By making a few assumptions, Max Planck was able to model these distributions:
- The radiation emitted was not continuous.
- The radiation emitted consisted of discrete packets of energy, known as QUANTA.
- A black body can only emit integer numbers of each quanta.

Quanta of EM radiation later became known as PHOTONS.

Planck suggested that the energy of these quanta was linked to the frequency of the light emitted.

$$E = hf$$

E - energy of the photon [J]
f - frequency of light [Hz]
h - Planck's constant $= 6.63 \times 10^{-34}\ Js$

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

REMINDER

Planck postulated that photons:
- Carry DISCRETE amounts of energy
- When they interact with matter they are absorbed or emitted AS WHOLE QUANTA.

Photoelectricity

In 1902, Phillip Lenard conducted an experiment with visible and ultraviolet light. He found that when incident on a sheet of metal, some of the incident waves could cause electrons to be emitted. These are known as PHOTOELECTRONS, released by the PHOTOELECTRIC EFFECT.

The observation made were:

1. Emission of photoelectrons ONLY occur if the frequency was above a minimum value. This became known as the THRESHOLD FREQUENCY. This was dependent on the type of metal used.
2. The emission of photoelectrons happens almost immediately after the metal is illuminated.
3. Above the threshold frequency, the number of photoelectrons emitted per second is proportional to the INTENSITY of the incident light.

INTENSITY
The energy incident on a surface per unit time per unit area $[W\,m^{-2}]$

INTENSITY = Number of photons incident per unit area per second x Energy of a single photon

4. The photoelectrons emitted have a range of kinetic energies, from zero up to a maximum value.
5. Above the threshold frequency, the maximum kinetic energy depends on the FREQUENCY of the incident light. (but is unaffected by the INTENSITY).

Failure of Wave Theory

The wave theory of light of light cannot explain the experimental observations of the photo-electric effect.

According to the wave theory of light, electrons in the metal would absorb energy gradually and continuously, when the electrons acquire sufficient energy they could overcome the electrostatic attraction of the ions in the metal, allowing them to be emitted:

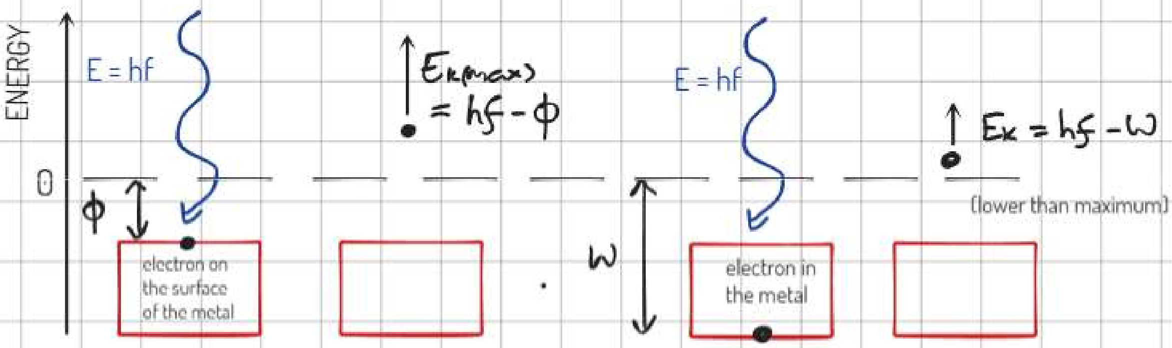
1. There would be a time delay between the metal being illuminated and photoelectrons being emitted, there should not be any instantaneous emissions of photoelectrons. ✗
2. According to the wave theory of light the intensity of light depends on the amplitude of the light waves. ✗
3. There would be no threshold frequency as even light of low frequency would eventually be able to emit photoelectrons, in a reasonable time, provided the amplitude of the light waves was high enough. ✗
4. Increasing the intensity of the light could increase the energy delivered to photoelectrons, increasing the maximum KE of photoelectrons. ✗

Along came Einstein

Einstein assumed that the incident light was composed of a BEAM OF PHOTONS.

When interacting with the metal, each photon could be reflected, or ABSORBED BY A SINGLE ELECTRON.

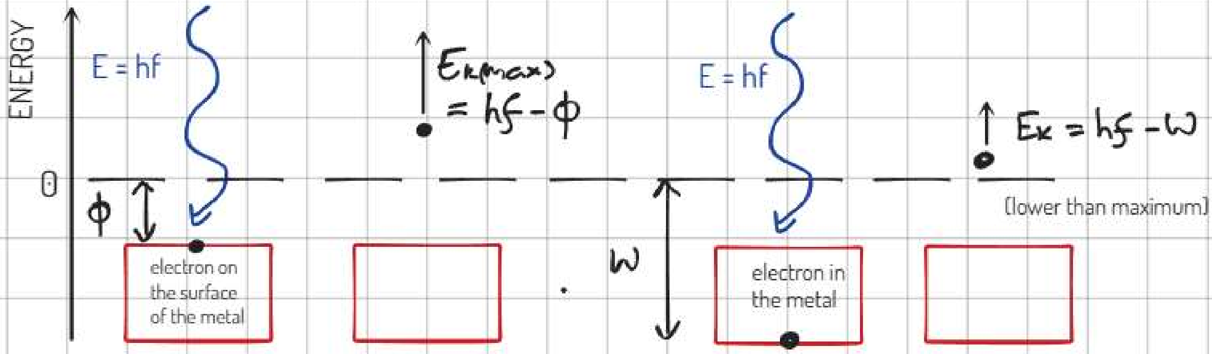
This means that as soons as one electron interacts with one photon (provided that photon had enough energy) the electron would be immediately emitted. The kinetic energy of the emitted electron would depend on the frequency of the photon it has absorbed. And the number of electrons emitted would depend only on the number of incident photons.



ϕ is the WORK FUNCTION. This is the MINIMUM energy required to remove an electron from the SURFACE OF THE METAL.

Electrons emitted in this way have MAXIMUM KINETIC ENERGY.

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



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When illuminated by MONOCHROMATIC LIGHT (single frequency) all photons transfer the same amount of energy when a single photon is absorbed by a single electr

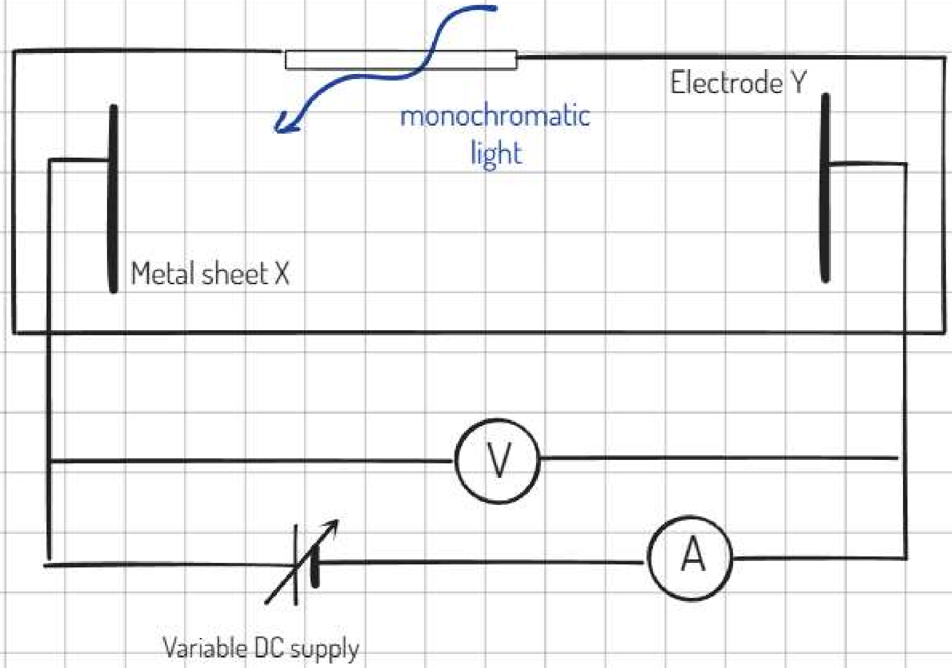
Electrons can escape the metal if the energy of the photon is sufficiently high, with the excess being stored as kinetic energy in the liberated electron.

Different electrons within the metal start with different energies. The closer to the surface of the metal the electrons are located, the MORE ENERGY they have. This means they require a LOWER ENERGY to be LIBERATED.

Electrons ON THE SURFACE of the metal require the MINIMUM AMOUNT OF ENERGY to be emitted (this is called the WORK FUNCTION). These electrons will have MAXIMUM KINETIC ENERGY.

Electrons liberated from other parts of the metal may require more energy, leading to a range of kinetic energies across emitted electrons.

Experimental Verification of Einstein's Explanation



The sheet X is illuminated with monochromatic light. Photoelectrons are emitted with a range of kinetic energies. Some of these photoelectrons travel to electrode Y, causing a current to flow between X and Y.

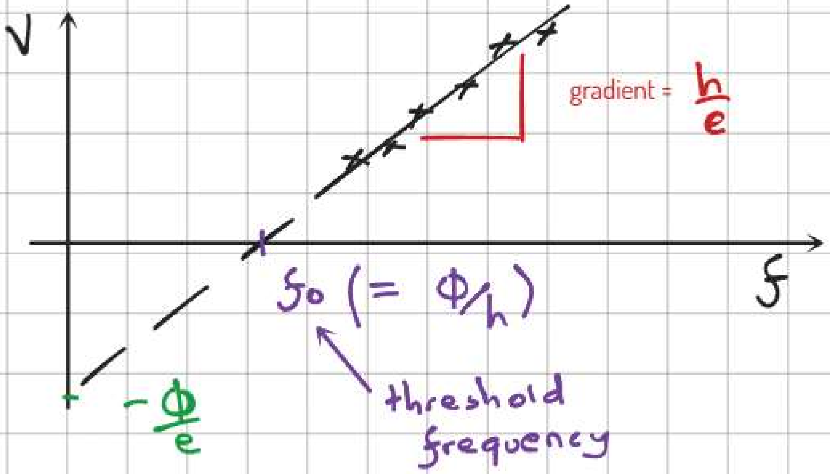
A potential difference is applied between Y and X. This produces and electric field between the plates and the pd was increased until current dropped to zero. This means that even the electrons with maximum kinetic energy were unable to reach Y.

This is called the STOPPING VOLTAGE.

We can apply the law of conservation of energy here:

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

LOSS IN KE — GAIN IN PE $(E = QV)$



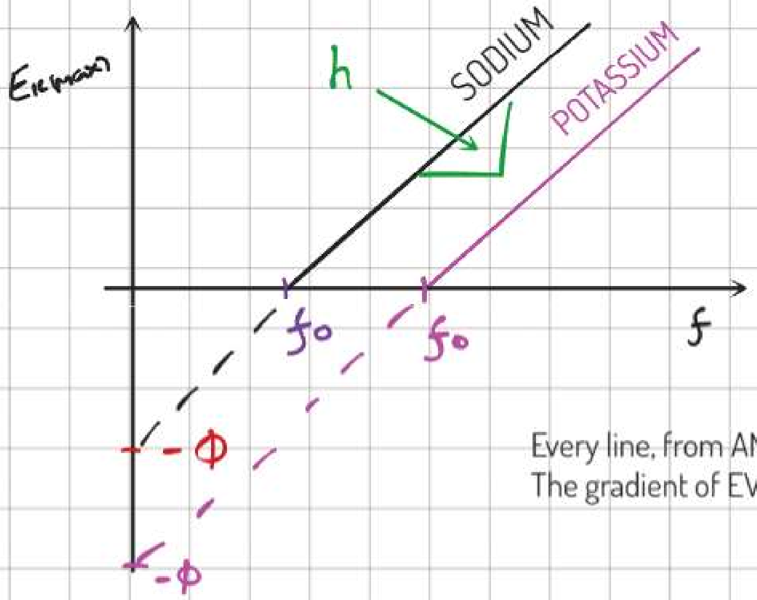
$$hf = \phi + \frac{1}{2}mv_{max}^2$$

$$hf = \phi + eV_s$$

$$V_s = \frac{h}{e}f - \frac{\phi}{e}$$

$$y = mx + c$$

We can also plot the data in terms of the maximum kinetic energy of the electrons.



$$hf = \phi + E_{k(max)}$$

$$E_{k(max)} = hf - \phi$$

$$y = mx + c$$

Every line, from ANY METAL will be PARALLEL.
The gradient of EVERY LINE will be h.

Light

In order to explain the photoelectric effect, Einstein suggested that light was not just a wave (as described by classical electromagnetic theory) but also a particle.

Light can undergo reflection, refraction, diffraction and interference like any other wave and that it has wavelength and frequency. But light can also only be emitted and absorbed in discrete quanta, like a particle.

These quanta are called photons, and described by:

$$\boxed{E = hf} \qquad h = 6.63 \times 10^{-34}\, Js$$

So light is said to be simultaneously a wave and a particle, it experiences wave-particle duality.

De Broglie's Hypothesis

In De Broglie suggest that if light can be a particle, so surely, particles can be waves...

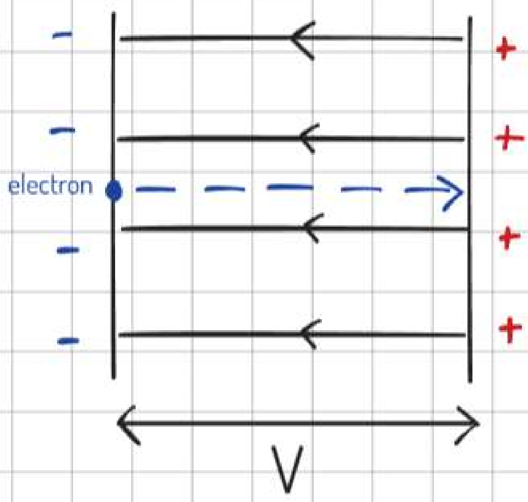
He suggested that particles could have a wavelength, and determined that these electron waves could be described with:

$$\boxed{\lambda = \frac{h}{p}} \qquad h = 6.63 \times 10^{-34}\, Js$$

$$p = momentum\ of\ particle$$

The wavelength of an electron

An electron is accelerated between two oppositely charged electrodes with a pd between them.



Lets begin from conservation of energy:

$$Gain\ in\ KE = Loss\ in\ PE$$

OR

$$\frac{1}{2}mv^2 = eV$$

$$mv^2 = 2eV$$

$$m^2v^2 = 2meV$$

$$mv = (2meV)^{1/2}$$

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

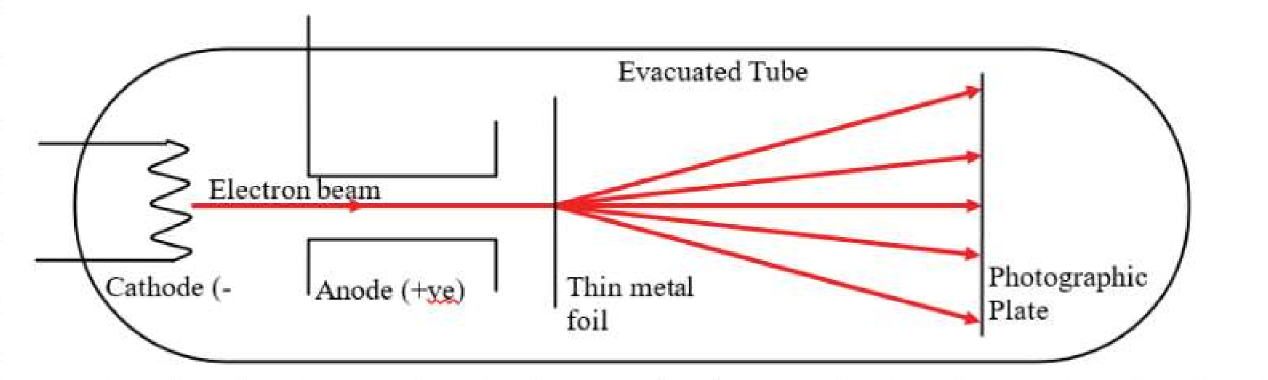
$$\lambda = \frac{h}{(2meV)^{1/2}}$$

$$\lambda = \frac{6.6 \times 10^{-34}}{(2 \times 9.11 \times 10^{-31} \times 1.6 \times 10^{-19} \times 100)^{1/2}}$$ for 100V

$$= 1.2 \times 10^{-10} m$$ approximate radius of an atom

Electron Diffraction

In 1928 experimental evidence supporting De Broglie's idea of electron waves was published.



Electrons were accelerated through a perforated anode before striking a thin metal foil and diffracting onto a photographic plate.

They produced a series of rings of different intensities arising from interference. The wavelength of the electrons was consistent with De Broglie's predictions.

The electron, like light is considered to have a wave-particle duality.

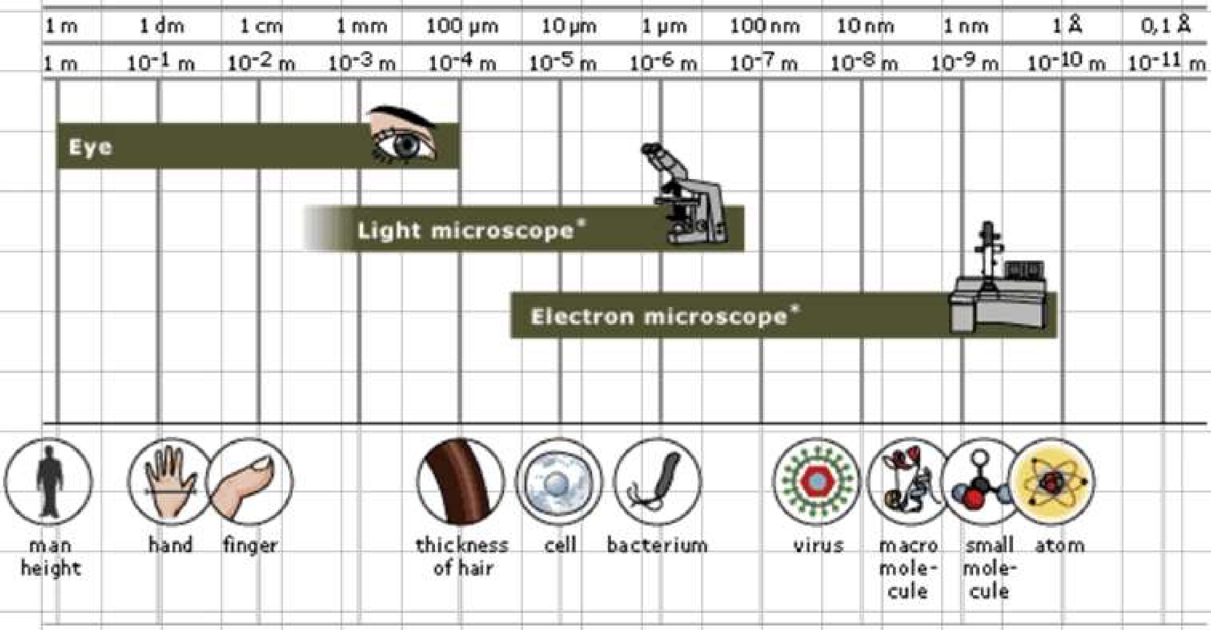
Other particles

All particles, even atoms and molecules should be able to exhibit wave-particle duality. This even applies to macroscopic collections of atoms.

Calculate the De Broglie wavelength of Andrew (82 kg) at a top speed of 8.5m/s
$\lambda = \frac{h}{mv} = \frac{6.63\times10^{-34}}{82\times8.5} = 9.5\times10^{-37}$ m   It is unlikely that a human being could fit through a gap comparable to their wavelength

In quantum mechanics, theory treats all particle and waves as PROBABILITY WAVES. They determine the probability of a particle being found in a given place.

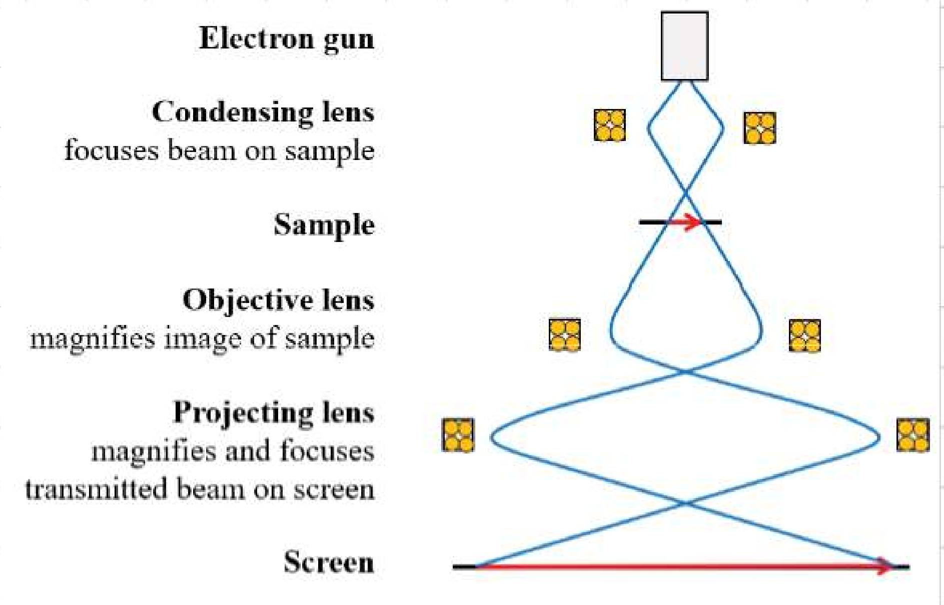
Electron Microscopy

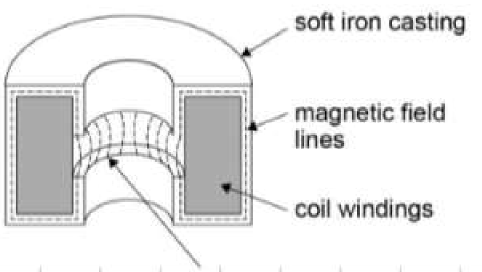


TEM

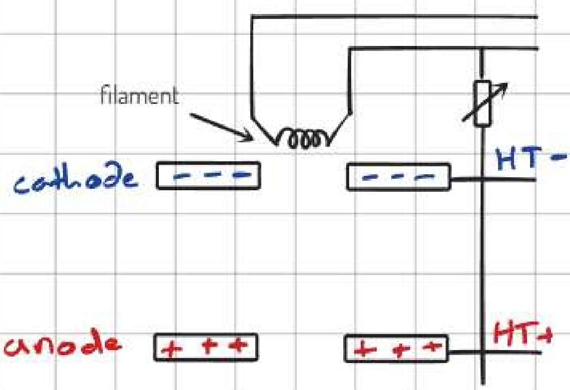
Transmission Electron Microscopy was developed in 1931 as a way of increasing the resolving power of images beyond that of visible microscopes.

This involves producing and directing an electron beam onto a target, using a series of 'lenses' to focus and magnify the image produced.





The 'Electron Gun'



Electrons are emitted from the heated filament.
The current in the beam is around 1 microamp
The electrons are accelerated across a high pd between the anode and cathode.

$$E_k \text{ gain} = E_p \text{ loss}$$

$$\frac{1}{2}mv^2 = eV$$

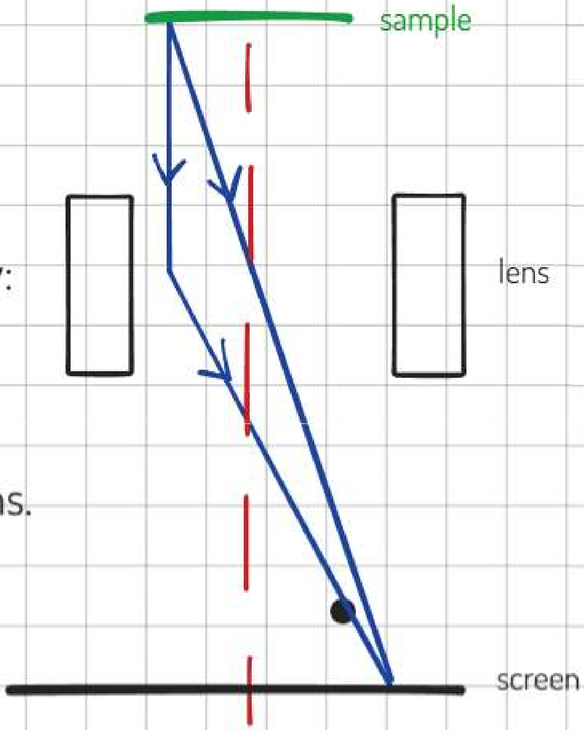
$$\frac{1}{2}\frac{p^2}{m} = eV \quad \text{so} \quad p^2 = 2meV$$

$$\boxed{\lambda = \frac{h}{(2meV)^{1/2}}}$$

Note: above 100kV some relativistic adjustments will be needed for the mass of the electron.

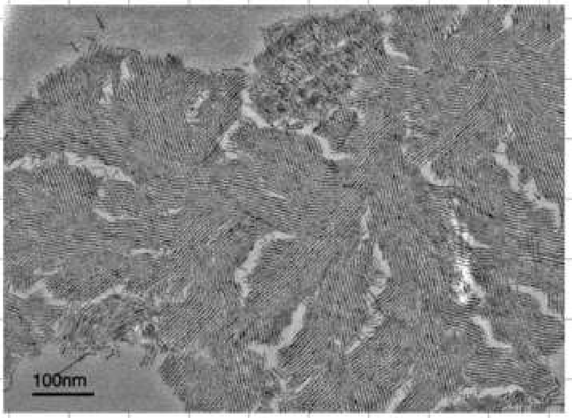
The Magnetic Lenses

Electrons passing near the inner edge of the lens is deflected towards the axis of the microscope.
Electrons passing through the centre are undeflected.



The RESOLUTION of the image can be changed by:
- Increasing the accelerating potential difference.
- This increases the speed of the electrons.
- This increases the momentum of the electrons.
- This DECREASES the wavelength of the electrons.
- Improving the resolution of the image.

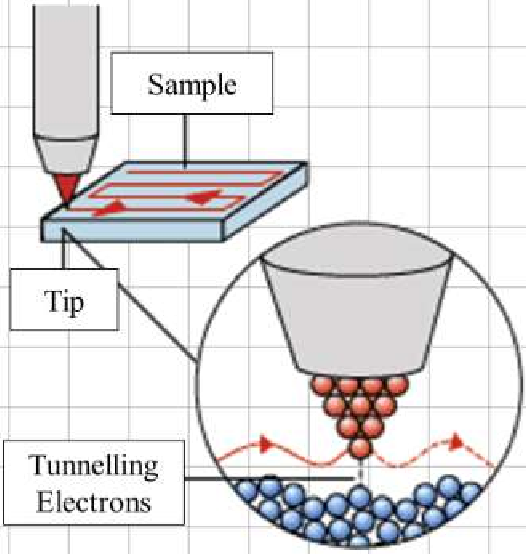
Limitations



- The sample needs to be very thinly sliced.
- The sample needs to be studied in a vacuum.
- The sample can be damaged by the passage of the electrons.
- There will be a range of speeds in the electron beam which limits resolution as the radius of curvature of an electron in a magnetic field depends on its speed.

STM

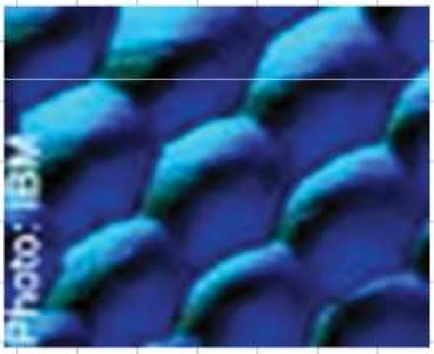
A Scanning Tunnelling Microscope studies the structure of a surface using a tip which scans the surface of a material.



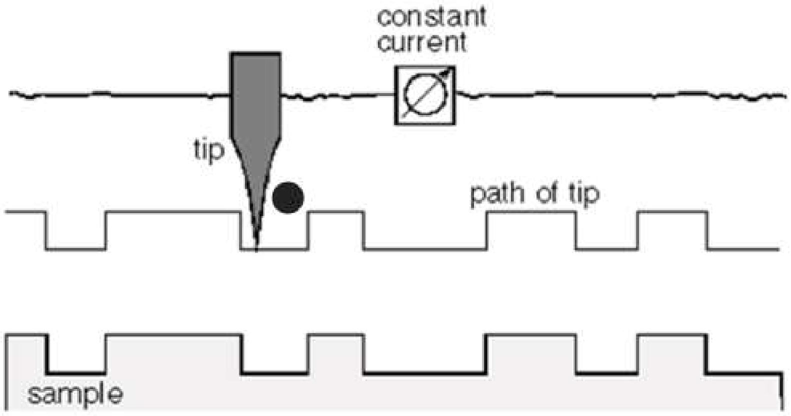
Electrons behaving like waves are able to cross the gap between the tip and the sample, despite not having sufficient energy to do so.

This is called QUANTUM TUNNELLING.

The size of the current depends on the distance between the tip and the sample. The bigger the distance, the smaller the current.

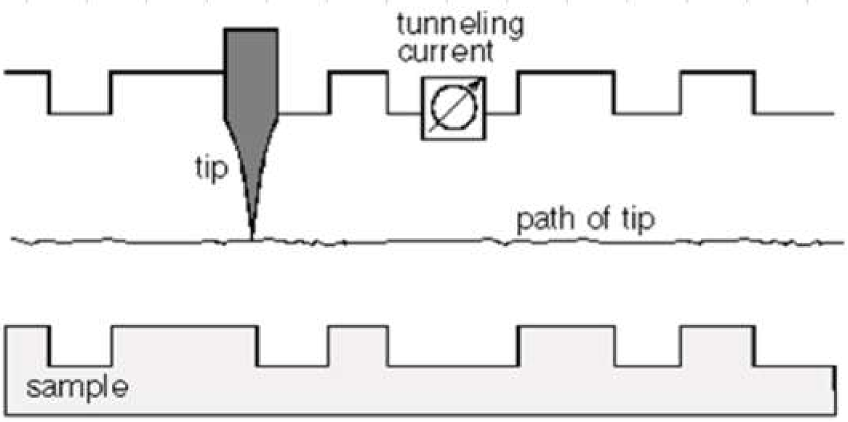


There are two different modes.



Constant Current Mode

- The tip is moved up and down as scans across the sample.
- This keep the current between the tip and the sample constant.
- The tip stays a constant height above the sample, to within $\pm 10^{-12}$ m .
- The position of the tip is recorded and the used to build up an image of the sample.



Constant Height Mode

- Tip travels across the sample in a horizontal plane.
- The current changes depending on the distance to the sample.
- The current is measured as the tip scans across the sample
- The current is used to construct and image of the surface
- This mode is used when the distance between gaps is small and the microscope needs to respond to rapid changes in profile