1. Increased understanding of cathode rays led to the development of television

- explain why the apparent inconsistent behaviour of cathode rays caused debate as to whether they were charged particles or electromagnetic waves

Cathode rays were observed to have properties of both charged particles and electromagnetic waves. Some (Goldstein, Hertz) thought that cathode rays were electromagnetic waves while others (Crookes, Thomson) thought cathode rays were formed by charged particles moving at great velocity.

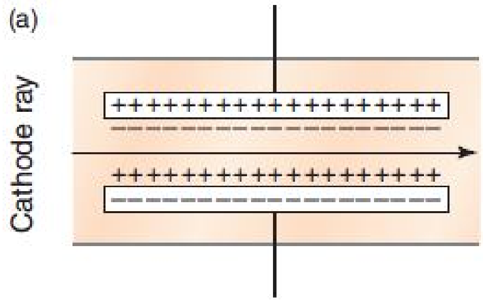
Cathode rays travelled in straight lines and if an opaque object was placed in their path, a shadow of that object appeared. This seemed to suggest cathode rays were waves, but charged particles can also travel in straight lines and be stopped by an object. Particle supporters suggested that the rays had momentum and mass since they turned small paddlewheels placed in the path of rays. However, wave advocators said that a radiometer also turned under light.

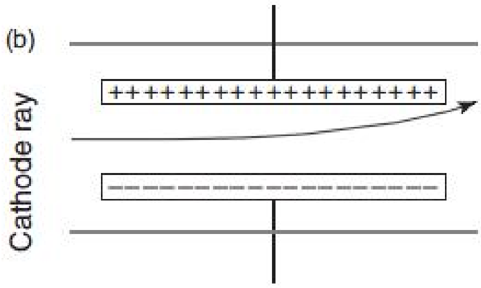
Remaining evidence for them being waves is that they can pass through thin sheets of metal foil without damaging them. And for particles, evidence is that they were obviously deflected by magnetic fields and they travelled considerably more slowly than light.

The main restriction for the charged particle theory was the absence of deflection in electric fields as shown by Hertz. But Thomson found that within the tube, cathode rays ionised the gas, and ions were attracted to the plate with opposite charge. So the ions neutralised the charge on the plate, allowing the cathode rays to pass by unaffected - (a).

Plates had to be sealed within the tube, and after evacuating air from the tube, Thomson used a tube with more complete vacuum than Hertz, and observed deflection of cathode rays due to an electric field, towards the positive plate - (b). This proved beyond doubt that cathode rays were not electromagnetic radiation but streams of negatively charged particles (electrons).

But the ability for cathode rays to penetrate thin metal foil without damaging them was still unexplained due to inadequate knowledge of the nature of atoms.





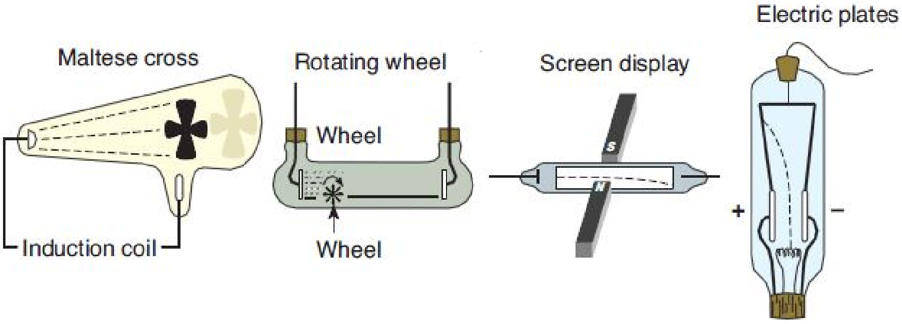
The scientific method was used to solve problems as observations from experiments are interpreted and a hypothesis is developed to explain what is thought to be happening. The inconsistent behaviour of cathode rays demonstrate limitations in experimental design, and opposing models arose. However, the argument is eventually resolved either by improved experiments or with greater understanding of the phenomenon. As seen in Thomson's breakthrough.

explain that cathode ray tubes allowed the manipulation of a stream of charged particles

A cathode ray tube (or discharge tube) is a sealed glass tube from which most of the air is removed by vacuum pump. A cathode and anode is sealed within tube, making electrical connections through the glass and connected to a high voltage source. An electron beam travels from the cathode to the anode, with little obstruction from gas particles, as high voltage is applied across electrodes inside the evacuated glass tube.

The stream of particles can be manipulated by the use of:

- An electric field can be made when two charged parallel plates of opposite polarity are separated by a small distance. The electric field can accelerate electron beams to high velocities or result in parabolic deflection towards the positive plate.
- An external magnetic field (i.e. from permanent magnets) can manipulate the stream of charged particles such that the cathode ray experiences a circular deflection, accelerating in a direction perpendicular to the magnetic field.
- Placement of solid objects in the vacuum tube produces some effects:
    - Maltese cross produces a shadow
    - A paddlewheel rotates when placed between the cathode and anode.



To observe the path of rays through the tube, a rectangular metal plate covered in zinc sulphide can be placed inside the tube. It has a horizontal slit cut into the end nearest the cathode and the plate was slightly bent so that cathode rays formed a horizontal beam. When cathode rays struck this material it appeared fluorescent and showed the path of the rays through the tube.

perform an investigation to demonstrate and identify properties of cathode rays using discharge tubes:
- containing a maltese cross
- containing electric plates
- with a fluorescent display screen
- containing a glass wheel
- analyse the information gathered to determine the sign of the charge on cathode rays

Aim: <According to dot point> Diagrams: <Above>

Maltese Cross

A Maltese Cross is placed inside the discharge tube in the path of the cathode ray.

A shadow of the Maltese Cross is observed, meaning that cathode rays travel in a straight line, causing a shadow of the object to be formed. It's seen that cathode rays cannot penetrate metal.

Electric Plates

Electric plates are sealed inside the cathode ray, and when a current is through the plates, a deflection of the cathode ray towards the positive plate was observed proportional to the current.

This demonstrates that cathode rays are deflected in a parabola under the influence of an electric field towards the positive plate, indicating it is a negatively charged particle.

Fluorescent screen display

The fluorescent screen is placed inside the cathode ray tube and fluoresced as the ray travels through it, indicating the path of the ray. The ray travelled straight towards the cathode if there weren't magnets providing an external magnetic field.

However, when there is a magnetic field, cathode rays are deflected by a force according to the right hand palm rule (thumb pointing in opposite direction).The deflection is in the arc of a circle (though curved screen may affect the curvature).

This demonstrates that cathode rays are charged particles which are deflected by a magnetic field, and cathode rays travel in a straight line otherwise.

Paddle Wheel

A paddle wheel is placed inside a discharge tube. It's observed that it rotates when the cathode ray tube is turned on. Salts on the paddle wheel glowed different colours when exposed to cathode rays.

This demonstrates that cathode rays transfer momentum to the paddle wheel. Hence, they have momentum and mass as the paddle wheel turns. And cathode rays also cause different salts to fluoresce different colours.

In all these experiments, it's revealed that cathode rays caused **glass to fluoresce green.**

- perform an investigation and gather first-hand information to observe the occurrence of different striation patterns for different pressures in discharge tubes

To observe the effects that different gas pressures have on an electrical discharge passed through a discharge tube, we connect a DC power source to an induction coil via leads.

The negative terminal of the induction coil is attached to the cathode of the discharge tube, and the positive terminal to the anode. Set the power source to correct settings (i.e. 6 volts) and turn it on. Sketch a diagram of the pattern observed in the tube and describe it. Repeat the above procedure using discharge tubes of different pressure. (tubes to be used: 40mmHg, 10mmHg, 6mmHg, 3mmHg, 0.14mmHg, 0.03mmHg).

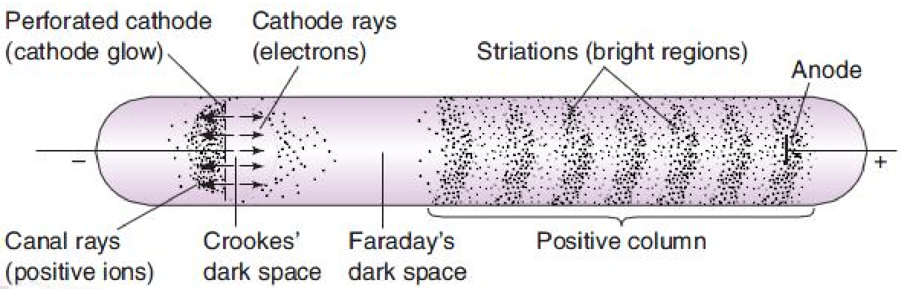
The induction coil produces high voltage, which is applied across terminals inside the discharge tubes. The electrons pass through the gas in the tube, exciting electrons in the atoms of the gas contained in the tube. When discharge tubes are evacuated to different air pressures, the different density of the gas particles means different nature of interaction between electrons and atoms. Therefore, different effects were produced and observed.

The first effect is a steady luminous discharge (glow discharge) as a bright luminous region (positive column) occupying most of the tube appears to start from the anode.

The lower the pressure, the faster the electrons accelerate before colliding with gas particles. So as the pressure lowers, the positive column is broken up into a series of bands or striations. These striations are separated by 'dark spaces'. Near the cathode, a weaker glow can also be seen.

Finally, at pressures of 0.03mmHg, the entire tube is occupied by dark space, and a green glow appears in the glass at the end of the discharge tube opposite the cathode.

Colours of discharge depends on the gas used.



The dark spaces are named after some of the scientists who examined them.

- identify that moving charged particles in a magnetic field experience a force

The motor effect identifies that a current carrying conductor in a magnetic field experiences a force. However, this can be reduced to the case of a single moving charged particle moving through a magnetic field. Therefore, a moving charged particle in an external magnetic field also experiences a force. The direction for such a force can be determined with the right hand palm rule as for current-carrying conductors, with the thumb pointing in the direction of moving positive charge.

- describe quantitatively the force acting on a charge moving through a magnetic field

$$F = qvB \sin\theta$$

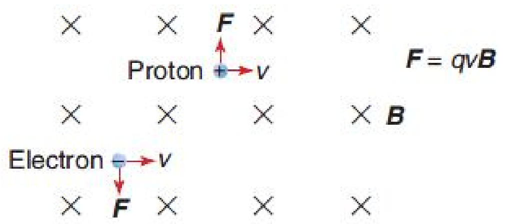
- *Where F is the force on the charged particle due to the magnetic - in Newtons*
- *And q is the charge - in coulombs*
- *v is the velocity of the charged object - in ms^{-1}*
- *B is magnetic field flux density - in Tesla*
- *Θ is the angle between the velocity of the charged particle and the* magnetic field.

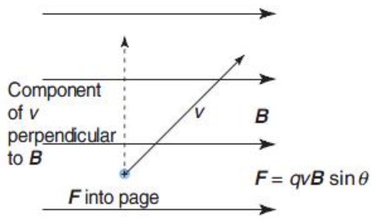
Quantitatively, if a particle with charge *q* (coulomb)is moving with velocity *v* (ms^{-1}) perpendicularly to a magnetic field of strength *B* (Tesla), then the particle will experience a magnetic force F (Newtons), given by F=*qvB*

The direction is determined by right hand palm rule as described above.

However, if velocity of the charged particle is at an angle Θ to the magnetic field, the force is given by F=*qvB* sinΘ. When applying right hand rule in these situations, use the component of velocity perpendicular to B as the direction of charged particle.

Note, if particle is travelling parallel to the magnetic field, then it experiences zero force as Θ=0º.





Hence, the charged particle experiences circular motion with the magnetic force acting as the centripetal force.

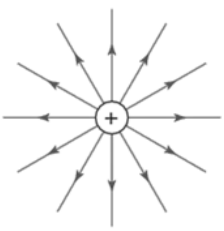
- As mass (m) and velocity (v) of the particle increases, the radius of the circle also increases.
- As magnetic field strength (B) and charge (q) increases, the radius of the circle decreases.

If the particle enters the field with an angle at an angle other than perpendicular to the field line, it will produce a helical motion.

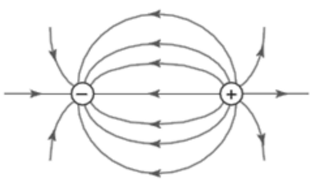
- identify that charged plates produce an electric field

An electric field exists in any region surrounding an electric charge and is one in which a charged particle experiences a force. An electrically charged plate produces an electric field and would exert a force on external charged particles resulting from charge repulsion or attraction, the force inversely proportional to distance according to inverse square law.

- discuss qualitatively the electric field strength due to a point charge, positive and negative charges and oppositely charged parallel plates



(a) Electric field around a single positive charge



(b) Opposite charges

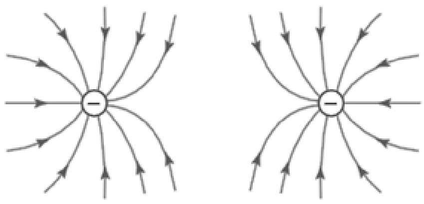
There are two types of charge, positive and negative. The electric field has both strength and direction, and similarly, Faraday's 'lines of force' represent the magnitude and direction of the electric field.

- The electric field strength is the relative amount of force a charged particle experiences in an electric field.
- The direction of the electric field is defined as the direction of force a positive charge experiences when placed in an electric field.

Since like charges repel, and opposite charges attract, this is reflected by the direction of lines of force radiating from the centre of the charge. For a positive charge, lines of force radially leave the centre of charge, while for a negative charge, lines of force are directed radially into the centre of the charge.

Since the lines of force are radial, then the further from a point charge, the less the electric field strength. Several applications to the interpretation of lines of force are:

- Field lines begin on positive charges and end on negative charges
- Field lines enter and exit at right angles only
- Field lines never cross
- More field lines located in the same area result in stronger magnetic fields



(c) Like charges

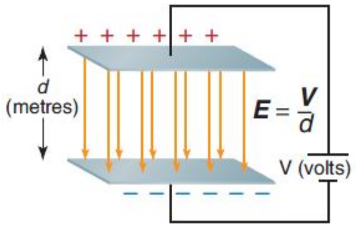
- Field lines close together represent strong fields
- Field lines well separated represent weak fields
- A positive charge placed in a field experiences a force in the direction of the arrow
- A negative charge placed in the field experiences a force in the direction opposite to the arrow.

Interaction between two point charges creates a resultant field which equals the sum of all component fields.

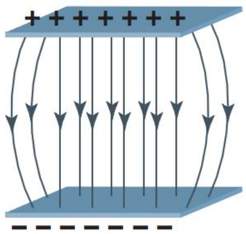
Two charged parallel plates of opposite polarity creates a region in which an uniform electric field exists given that the length of the plates is significantly larger than the distance between them. The field will be uniform except at the edges. Charged particles within this electric field experiences a net force towards one plate. <see pictures below>

Or when potential difference is applied across two parallel plates such that they are oppositely charged and given that the length of the plates is significantly greater than the distance between them. Then an uniform electric field will be produced, except at the edges where it will be slightly curved.

- describe quantitatively the electric field due to oppositely charged parallel plates



E is proportional to the potential difference, V, between the plates. But inversely proportional to distance, d, between the plates.



The electric field between the two parallel plates is the same at all points between the plates and at right angles to the plates everywhere within the region.

The magnitude (or intensity) of the electric field is determined by finding the force acting on a unit charge placed at that point. This can also be rearranged with force as the subject.

$$E = \frac{F}{q} \quad or \quad F = Eq$$

Where E = electric field intensity in Newtons per coulomb
F = electric force in Newtons, N
q = electric charge in Coulombs, C

And since potential difference is the change in potential energy per unit of charge moving from one point to another

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

Therefore, the amount of work is given by:

$$W = qV$$

We also see that the work done by a force is the product of the force and the distance moved, d; i.e. W = Fd. Therefore, Combining the above formulas:

$$qV = W = Fd = qEd$$

Hence we deduce that:

$$V = Ed \quad or \quad E = \frac{V}{d}$$

Where V = potential difference in volts
d = distance of separation between two plates

A small positive charged particle released next to a positive plate experiences a force, accelerating the charge. Noting that work done is equal to the gain in energy, the charge will increase in kinetic energy:

$$W = qV = \frac{1}{2}mv^2$$

solve problem and analyse information using:

$B = 2.0 \times 10^{-2}$ T

Effects of magnetic fields on electrons

solve problem and analyse information using:

$$F = qvB\sin\theta$$

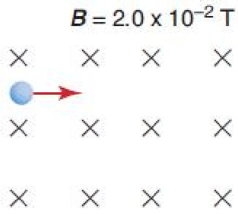
$$F = qE$$

and

$$E = \frac{V}{d}$$

ALWAYS remember to convert to SI units.

Include units AND directions in final answer, noting significant figures.



Effects of magnetic fields on electrons

An electron charge -1.6×10^{-19} C is projected perpendicularly into a region where a magnetic field exists (as in diagram). If the velocity of the electron is 2.5×10^{4} ms^{-1} determine:

a. Force on the electron the instant it enters the magnetic field
[Sol] $F=qvB\sin\theta$, $q = -1.6\times10^{-19}$C, $v = 2.5\times10^{4}ms^{-1}$, $B = 2.0\times10^{-2}$T
Therefore, $F = (-1.6\times10^{-19})(2.5\times10^{4})(2.0\times10^{-2})$
=8.0x10-17N downwards

b. Shape of the path which the electron follows
[Sol] The path the electron follows will be circular as magnetic force acts perpendicular to the velocity.

Electric field strength

What is the electric field strength between two parallel plates separated by 5.0mm if a potential difference of 48V is applied across them.
[Sol] $E = V/d$, $V = 48V$, $d = 5.0mm = 5.0\times10^{-3}m$. Therefore, $E=V/d= (48)/(5.0\times10^{-3}) = 9600Vm^{-1}$ or NC^{-1}

Moving charge through potential difference

How much work is done by a charge of 3.6μC through a potential difference of 15 volts.
[Sol] $W = qV$, $q=3.6\mu C = 3.6\times10^{-6}C$, $V = 15V$. Therefore, $W = (3.6\times10^{-6})(15) = 5.4\times10^{-5}$ Joules

Velocity of charge between two plates

Two parallel plates are separated by a distance of 5.0mm. A potential difference of 200V is connected across them. A small object with a mass of 1.8×10^{-12}kg given a charge of 12μC. It is released from rest near the positive plate. Calculate the velocity gained as it moves from the positive towards the negative plate.
[Sol] $E = qV = (1/2) mv^2$, $q = 12\mu C = 1.2\times10^{-5}C$, $V = 200V$, $m = 1.8\times10^{-12}kg$
$v^2 = (2qV)/m = [2(1.2\times10^{-5})(2.00\times10^{2})]/1.8\times10^{-12}$, therefore, $v = 5.2\times10^{4}$ ms^{-1}.

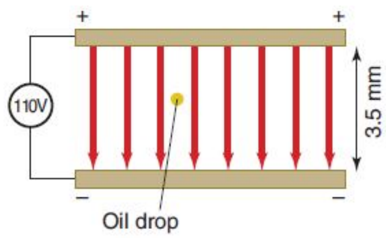
Field strength and charge on an oil drop

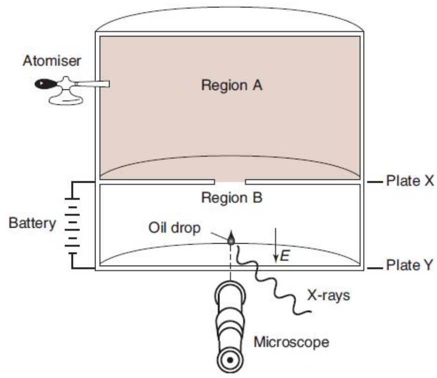
An oil drop of mass 6.8×10^{-6}g is suspended between two parallel plates separated by a distance of 3.5mm as shown in the diagram.

a. What is the electric field strength between the plates?
[Sol] $E=V/d$, $V = 110V$, $d = 3.5mm = 3.5\times10^{-3}m$
Therefore, $E = 110/(3.5\times10^{-3}) = 3.1\times10^{4}V\ m^{-1}$ down

b. What is the charge that must exist on the oil drop?
[Sol] Since the oil drop is suspended, electric force up is equal to weight force down. I.e. $qE = F = mg$
Therefore, $q = mg/E$, $m = 6.8\times10^{-9}kg$, $g = -9.8ms^{-2}$, $E = 3.1\times10^{4}Vm^{-1}$ down
$q = [(6.8\times10^{-9})(9.8)]/(3.1\times10^{4}) = 2.1\times10^{-12}C$

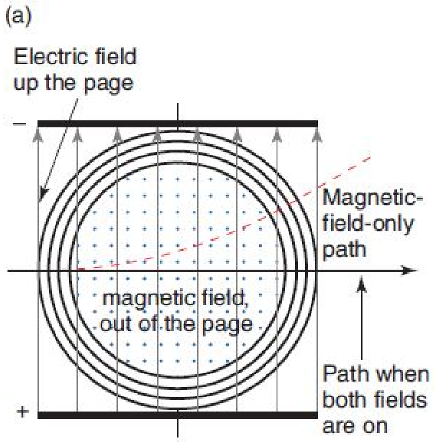
c. How many excess electrons must be present on the oil drop?
[Sol] Number = (Charge on drop)/(charge on electron)
= $(2.1\times10^{-12})/(1.6\times10^{-19}) = 1.3\times10^{7}$ electrons

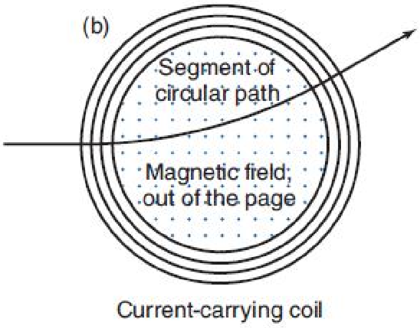




outline Thomson's experiment to measure the charge/mass ratio of an electron

Initially, scientists didn't know the charge or mass of an electron. As electrons are deflected by both a magnetic and electric field, Thomson investigated the effect of cathode rays passing through both fields.





He built a cathode ray tube such that cathode rays accelerated towards an anode and a thin electron beam passed through a hole. Charged parallel metal plates sealed within the tube (attached to a high voltage power source). Also, a pair of current carrying coils provided an external magnetic field such that the electric and magnetic fields were oriented at right angles to each other. This had the effect of producing forces that directly opposed each other as the electrons passed through.

Thomson varied the magnetic and electric fields until their opposing forces cancelled, leaving the cathode ray undeflected. (a), By equating the magnetic and electric force equations, Thomson was able to determine the velocity of cathode ray particles.

$$F = Eq = qvB$$

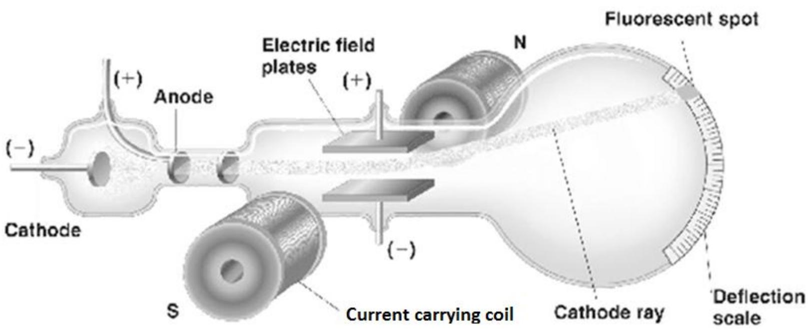
$$v = \frac{E}{B}$$

Then by applying the same strength magnetic field alone, the electrons in the cathode ray experienced circular deflection due to force applied by the magnetic field. (b), By equating the force due to the magnetic field to the centripetal forces, he found an expression for the charge to mass ratio of electrons.

$$F = \frac{mv^2}{r} = qvB$$

$$\frac{q}{m} = \frac{v^2}{r(vB)} = \frac{v}{rB} = \frac{E}{rB^2}$$

E and B are both known and the radius of circular path travelled by the electron can be determined using a ruler.
Therefore, Thomson determined the charge to mass ratios of cathode rays and all electrons had the same charge/mass ratio of $1.76\text{x}10^{11}$C kg^{-1}.

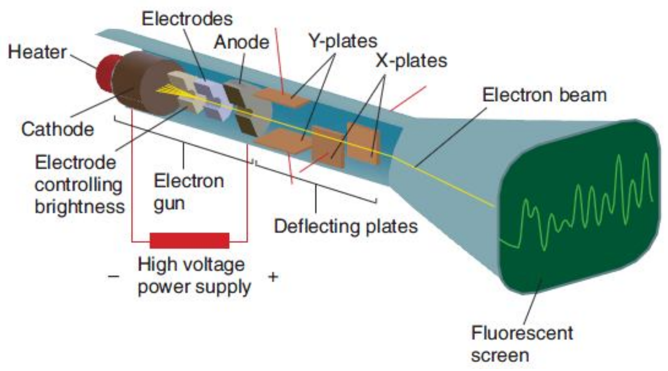


Regardless of cathode material or gases, cathode rays have a charge to mass ratio of $1.76\text{x}10^{11}$ C kg^{-1}. This is more than 1000 times that of the hydrogen ion (H^+), suggesting that either particles were very light, or very highly charged. Following this, Thomson produced his plum-pudding model, proposing that these particles were the constituents of atoms.

outline the role of:
– electrodes in the electron gun
– the deflection plates or coils
– the fluorescent screen
in the cathode ray tube of conventional TV displays and oscilloscopes

The cathode ray tube has many components:

- The electron gun consists of a heating filament heating the cathode and the hot cathode ejects electrons by thermionic emission. The electrons are in an electric field created by voltage difference between the cathode and anode, exerting a force on electrons and accelerating them through various electrodes. Firstly a cathode grid controls the number of electrons of the beam, controlling the brightness of the image. [By making the grid more negative in respect to the cathode reduces number of electrons]. Finally, only a stream of electrons pass through anodes with a hole, the electrons are accelerated as described above, and the anode also focuses them.



- Fast moving electrons then pass through two sets of deflection plates or coils are also set up in a cathode ray tube. **Television sets** generally use electric coils to produce magnetic fields which exert a forge on the negatively charged particles, controlling the movements of the electron beam. While **oscilloscopes** have two sets of parallel deflecting plates, charged to produce unidirectional electric fields exerting a force on the negatively charged particles in the desired direction. Either way, deflection plates or coils provide deflection along the x and y-axis, deflecting the electron beam vertically or horizontally to all points on the fluorescent screen.
    - Magnetic fields deflect electron beams to greater angles using magnetic deflection. The wider angle beam enables TV picture tubes to be shorter.

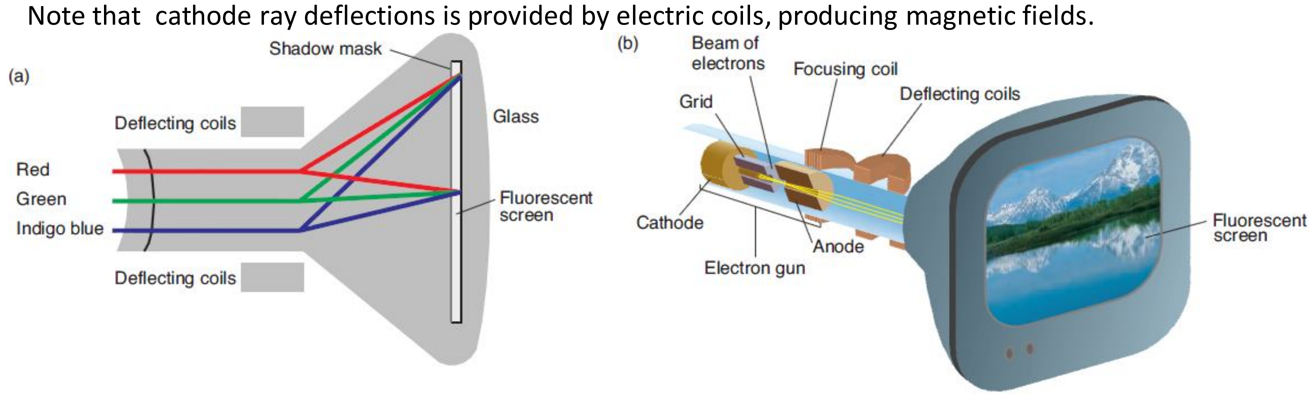
- Fast moving high energy electrons finally strike the glass screen coated with layers of fluorescent material (i.e. ZnS), their kinetic energy converted to light energy. Hence, the continuous sweep of the electron beam on screen produces visible output on the screen.

Television

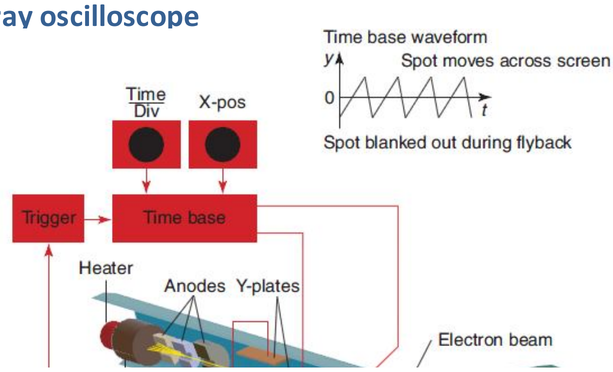
After signal is transmitted to the receiver, which directs the appropriate visual signal to one of three electron guns, each corresponding to one of the primary colours (red, green, blue). Dots of phosphorescent paint on the screen convert energy of electron beams into light. In colour TVs, phosphorescent dots come in primary colours, each electron gun stimulating its appropriate phosphor and the picture is reconstituted on screen by an additive process, and the many colours are formed from combinations of these three. After being excited, phosphorescence continues to emit light for a longer time, helping to minimise screen flicker.

The three electron beams scan the screen, coming from slightly different directions through holes in the shadow mask such that each beam of electrons can only hits the corresponding phosphor. The electrons sweep the screen in scans which takes one fiftieth of a second, so the brain does not see the screen flicker.

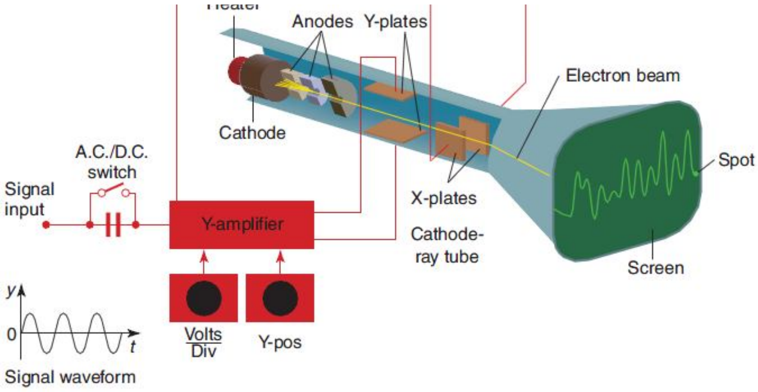
Note that cathode ray deflections is provided by electric coils, producing magnetic fields.



Cathode ray oscilloscope



The cathode ray oscilloscope is a powerful diagnostics tool and can display a variety of electrical signals. Deflections, produced by deflection plates, are in unison to voltage changes and the waveform displayed is directly influenced by the input voltage. The voltage is on the vertical axis controlled by vertical deflection plates. While time, being on the



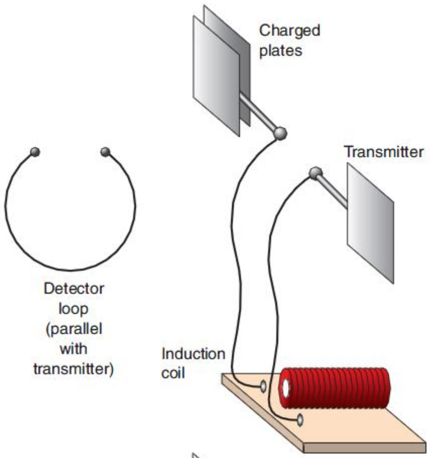
input voltage. The voltage is on the vertical axis controlled by vertical deflection plates. While time, being on the horizontal axis, is controlled by horizontal deflection plates. It is provided by a time base, allowing a variety of sweep rates, setting the time division on screen. Thus voltage can be plotted as a function of time, and complex waveforms or very short pulses can be displayed and measured.

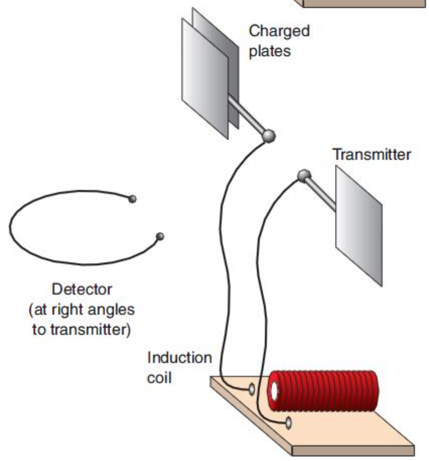
Compare structure and function of a CRO and CRT TV.
Both devices direct beam of electron to cause fluorescence on screen. Both use electron gun to accelerate electrons. However, in CRO, electron beam is directed by electric fields (produced by parallel plates), while in a TV it is by magnetic fields (produced by coils of wire).

CRO functions to examine how voltage signals change with time, a valuable tool for engineers and experimental scientists. Whereas, a TV produces moving image from signals encoded and sent using EM waves, becoming the world's most important form of mass media.

The reconceptualisation of the model of light led to an understanding of the photoelectric effect and black body radiation

- describe Hertz's observation of the effect of a radio wave on a receiver and the photoelectric effect he produced but failed to investigate





Maxwell's theory for electromagnetic waves predicted that:

- All electromagnetic waves (including light) must be transverse waves and propagate through space at the speed of light, estimated to be $3.11\times10^{8}ms^{-1}$.
    - As a non-uniformly changing magnetic field produces a changing electric field, in turn producing a changing magnetic field, etc.
- A full range of frequencies of electromagnetic waves should exist.

In 1886, Heinrich Hertz set out to verify these predictions with a series of experiments. He reasoned that electromagnetic waves other than visible and infra red radiation could be produced by an induction coil connected to two spherical brass electrodes, creating a rapidly oscillating electric field from rapid sparking between a gap between the electrodes. The electrodes were connected to two brass plates acting as an aerial system.

When a small length of wire was bent into a loop with a small gap, held near the sparking gap of the spherical electrodes, a spark would jump across the gap in the loop too. The sparking occurred synchronously and the loop wasn't connected to the source of electrical current.

Hertz theorised that the spark discharge oscillating back and forth between the brass electrodes set up changing electric and magnetic fields, propagating as an EM wave (as postulated by Maxwell). These were later known to be radio waves. When the waves reached the receiver, it caused oscillation of charges in the loop, resulting in the spark across the gap.

He initially observed the photoelectric effect during the experiment when the entire apparatus was placed in a darkened box and the max spark length on the receiver loop decreased. UV light assists electrons to jump the gap, but the glass panel between the transmitter and receiver absorbed UV radiation, reducing intensity of sparking in the receiving loop. However, when quartz, which doesn't absorb UV, is used as a shield, no drop in the receiving loop spark was observed.

Although he reported the observation, he failed investigated this effect further, nor make an attempt at explaining the phenomenon.

- outline qualitatively Hertz's experiments in measuring the speed of radio waves and how they relate to light waves

Wavelength of the wave was measured by setting up the receiver loop at intermediate angles to the transmitter, the interference of currents providing a measure of wavelength of radio waves.

Hertz showed radio waves can be reflected using metal mirror. But to definitively prove that these were waves like light, he showed their refraction, polarisation, interference and diffraction (properties unique to waves).

Refraction is shown when passing through a pitch prism. Polarisation by rotating the receiver loop: when receiving loop is parallel to transmitting gap, sparking in the receiver was at maximum and intermediate angles was proportionately less, showing no sparking in the when perpendicular.

Then waves of determined frequency from an oscillating circuit were followed 2 different measured paths: one being a direct beam from the transmitter interfering with the second reflected from a metal plate set at a small angle. Constructive and destructive interference results in a diffraction pattern showing separation of maxima and minima proportional to the wavelength of the disturbance. The longer wavelength of the radio waves meant determining it was easier than with light. By using $v=\lambda f$, he determined the speed of radio waves, corresponding with the speed of light predicted by Maxwell's equations ($3.11\times10^{8}ms^{-1}$) and Fizeau's experiments ($3.15\times10^{9}ms^{-1}$).

The waves observed had similar properties with light: reflection, refraction, polarisation and diffraction and travelled at the same speed ($c=3x10^8ms^{-1}$). Therefore, he reasoned the loop to be a detector of electromagnetic waves generated by the transmitter, providing the first strong experimental evidence for Maxwell's prediction that light was a form of transverse EM waves and the existence of an EM spectrum.

Important Points:
1. Maxwell's prediction - Electric --> Magnetic --> Electric fields (self propagating).
2. Hertz tests this hypothesis --> Spark, made from starts/stops of high voltage induction coil joined to two spheres with small gap.
3. Sparking in receiver means something was detected.
4. Series of experiments to verify these were indeed waves (reflected, refracted, polarised, diffracted) --> explain each in detail.
5. Worked out wavelength, note constructive destructive frequency. Knew frequency and determined speed.
6. Verified Maxwell's predictions

perform an investigation to demonstrate the production and reception of radio waves

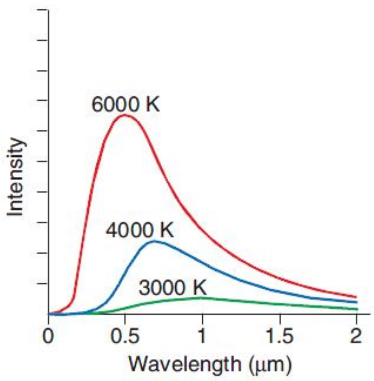
Aim: To produce and receive radio waves.
An induction coil acts to produce radio waves. Connect an induction coil and switch to a variable DC power supply. Long connecting leads should be used so that the switch is far away from the induction coil. Select the optimum voltage setting (i.e. C --> 6V).
The radio acts for the reception of radio waves. Turn on a radio, and set it to crackle at some frequency. Turn on the power supply, and close the switch for a brief moment. Record observations. If no effect is heard when switch is tapped, change the frequency.

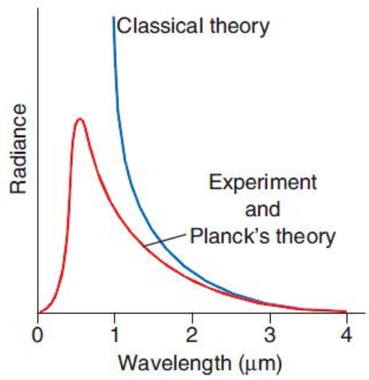
identify Planck's hypothesis that radiation emitted and absorbed by the walls of a black body cavity is quantised

Note: an ideal black body is a sphere with a tiny hole in it through which EM radiation enters.

It's known that there's a relationship between the temperature of a black body and the dominant wavelength. From experimental evidence, increase in temperature is accompanied by decrease in dominant wavelength (shift to left).
With classical physics based on thermodynamics, the predicted pattern of radiation didn't match experimental data. Although classical theory is correct for larger wavelengths, it predicts that radiation intensity of shorter wavelengths would increase to an infinite amount. This effect, called the 'ultraviolet catastrophe' violates the law of conservation of energy.
Planck's hypothesis explains the problem of black-body radiation. He invented quantum physics and proposed that radiation from a black body is not radiated or absorbed continuously, but all energy is radiated and absorbed in discreet packets (quanta). Hence, this explanation for the nature of radiation emitted treats the exchange of energy between the particles of the black body and the equilibrium radiation field is quantised.

Subsequently, electrons cannot receive and emit energy continuously. Quanta of energy were only absorbed or emitted only when electrons changed from one quantised energy level to another.





identify the relationships between photon energy, frequency, speed of light and wavelength:

$$E = hf$$

and

$$c = f\lambda$$

As with all waves, the speed of light (ms^{-1}) is the multiplication of the frequency (Hz / s^{-1}) and wavelength (m) of the wave. The speed c is a constant of $3x10^8$ ms^{-1} in vacuum.

$$E = hf$$

The energy (J) of a quantum is directly proportional to its frequency (Hz or s^{-1}) This constant of proportionality is Planck's constant ($6.626x10^{-34}$ Js / 6.63 $x10^{-34}$).

$$c = f\lambda$$

The energy of one quantum/photon of light of any wavelength is:

$$E = hf = h\frac{c}{\lambda}$$

solve problems and analyse information using:

$$E = hf$$

and

$$c = f\lambda$$

What is the energy of an ultraviolet-light photon, wavelength = $3.00x10^{-7}$m?
[Sol] c=fλ, therefore, f=c/λ
E = hf = (hc)/λ, h = $6.63x10^{-34}$Js, c = $3x10^8$ ms^{-1}, λ = $3.00x10^{-7}$m
E = [($6.63x10^{-34}$)($3.00x10^8$)]/($3.00x10^{-7}$) = $6.63x10^{-19}$ J

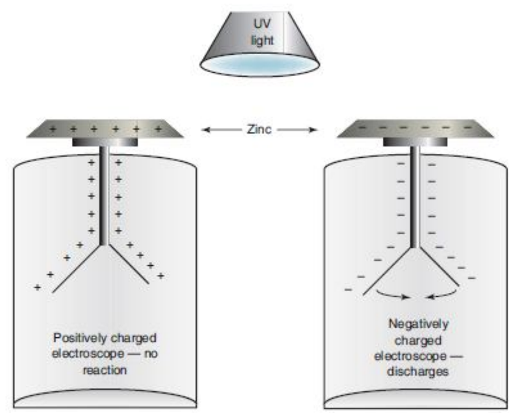
A beam of monochromatic light falls onto a cold, perfect black body, imparting 0.10mW of power to it. If the wavelength of the light is $5.0x10^{-7}$m, calculate:

a. The frequency of the light
[Sol] c = fλ, f=c/λ, c = $3.00x10^8ms^{-1}$, λ = $5.0x10^{-7}$m
f = ($3.00x10^8$)/($5.0x10^{-7}$) = $6.0x10^{14}$ Hz
b. The energy per photon for the light
[Sol] E = hf, h = $6.63x10^{-34}$, f = $6.0x10^{14}$ Hz
E = ($6.63x10^{-34}$)($6.0x10^{14}$) = $4.0x10^{-19}$J per photon
c. The number of photons per second striking the black body
[Sol] No. of photons per second
= Energy per second (watts)/energy for 1 photon
= $10^{-4}/4x10^{-19}$ = $2.5x10^{14}$

Some background on Photoelectric effect

Although Hertz failed to further investigate the photoelectric effect, Wilhelm Hallwachs did so by placing a clean plate of zinc on an insulated stand, attaching it by wire to a gold leaf electroscope. He found that a negatively charged electroscope leaked charge very quickly when exposed to UV light from an arc lamp or burning magnesium; whereas the control lamp experienced no such fast discharge as it was unexposed to UV.

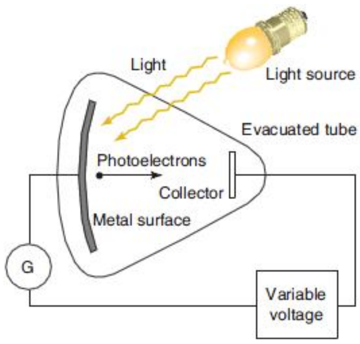
	UV lamp	Light
Negatively charged electroscope	Gold leaf collapses due to rapid discharge	No observable effect
Positively charged electroscope	No observable effect	No observable effect

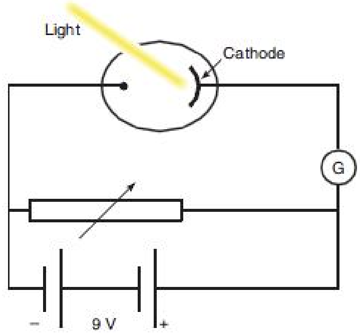


Later Thomson established the emission of electrons from a sheet of zinc metal when exposed to UV radiation. These were the same particles consisting cathode rays. He did this by enclosing the metal surface in a vacuum and exposing it to an UV source.

The new feature of this experiment is that electrons ejected from the metal by radiation rather than by the strong electric field used in the CRT.

Philipp von Lenard then studied the energy of emitted electrons when varying the intensity of the light used. He was able to adjust the light intensity of a carbon arc lamp, and photoelectrons emitted from the cathode struck the collector.



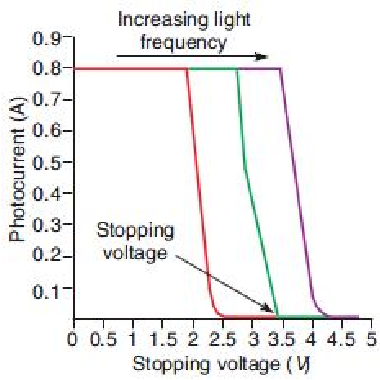


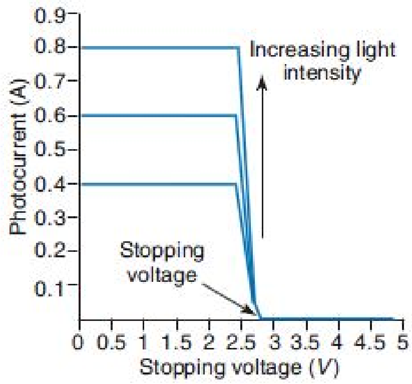
To measure the energy of emitted electrons, voltage is applied across the variable resistor and the collector is negatively charged to oppose the motion of photoelectrons. Hence only electrons ejected with enough energy could overcome this potential hill. Electrons reaching the opposite electrode creates a small current, measurable by a galvanometer. He found a well defined voltage where the current drops to zero, aka as the stopping voltage, V_{stop}.

By filtering out the arc light, he investigated the effect of different frequencies of the incident EM radiation on photoelectron emission.

From experimental data, Lenard observed that increasing the light intensity increases the number of electrons emitted, but there was no affect on the kinetic energy of the electrons.

Instead, max kinetic energy of electrons depends on frequency of the light illuminating the metal.





- identify Einstein's contribution to quantum theory and its relation to black body radiation

AND

- identify data sources, gather, process and analyse information and use available evidence to assess Einstein's contribution to quantum theory and its relation to black body radiation

AND

- explain the particle model of light in terms of photons with particular energy and frequency

Plank proposed a quantum theory approach to explain black body radiation curves by proposing that energy is not emitted or absorbed continuously, but in discreet packets (i.e. quanta). However, he simply believed that the quantisation of energy emitted from a black body was a mathematical trick to explain the experimental data.

Einstein not only agreed with Planck's explanation of black body radiation, but based on Planck's hypothesis, Einstein extended the concept of quantised energy to light waves. This contribution to quantum theory reasoned the energy from light waves can be treated as a stream of discontinuous quanta, called 'photons'.

A photon is the smallest amount of radiation energy possible at a particular frequency, hence a photon cannot transfer a part of its energy, but only all or none of it. The energy a photon has is proportional to its frequency: $E = hf$. As such, photons of higher energy corresponds with light of higher frequency or lower wavelength (i.e. violet end of the visible spectrum)

The photoelectric effect is a phenomenon where electrons are emitted from matter after absorption of energy from electromagnetic radiation (i.e. usually,

*The **threshold frequency** is such that above the frequency there is an emission of electrons, but below it, there is no photoelectric effect.*

Light intensity depends on the number

there is no photoelectric effect.

Light intensity depends on the number of protons.

Two beams of the same no. of photons have the same intensity even if the energy of each photon in the beams might be different. Intensity is defined as photons/area.

Input radiation	Result
Low intensity red light	No photoelectric effect
High intensity red light	No photoelectric effect.
Low intensity, low frequency UV	A few electrons emitted
Low intensity high frequency UV	Same no. of electrons with higher kinetic energy
High intensity, high frequency UV	Many electrons emitted with higher kinetic energy

The photoelectric effect is a phenomenon where electrons are emitted from matter after absorption of energy from electromagnetic radiation (i.e. usually, at least UV is needed). Hertz first observed this, but failed to investigate it further.

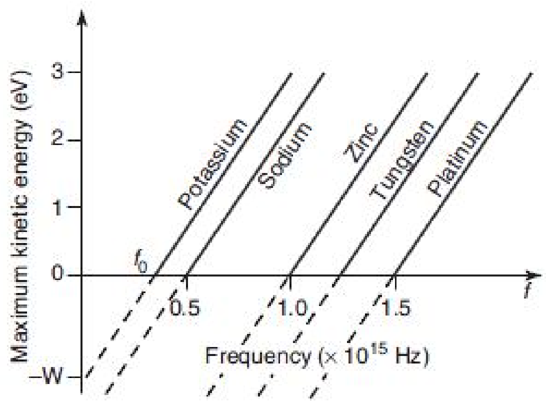
Classical physics assumed that emission is independent of requency and was unable to explain the photoelectric effect. It assumed that energy would be absorbed slowly over time, and electrons leave the metal surface when sufficient energy is acquired. In addition, it was thought that higher intensity means more energy would be imparted and electrons would have higher kinetic energy.

Instead, experimental data showed no time lag between light striking and the kinetic energy of electrons was constant despite different intensity. Under a certain frequency, no electrons would be emitted and classical physicists could not explain this threshold frequency.

However, Einstein's quantisation of the model of light proposed that one photon only hits one electron and either has or has not sufficient energy to eject it. The energy contained in the light photons (given by E=hf) must be equal to, or greater than, the energy required (work function) to overcome the forces holding the electron to the surface for electrons to be emitted from the metal surface. Since energy of a photon is proportional to its frequency (E=hf), the work function can be attained by light of sufficiently high frequency to overcome the threshold frequency. If the EM radiation illuminating the metal surface has frequency higher than the threshold frequency, energy of the incident photons is greater than the work function, producing the photoelectric effect - where additional energy of the photon above the work function energy level provides kinetic energy of the photoelectrons.

[Assessment] Therefore, Einstein's contribution to explain the photoelectric effect using the quantum nature of light has expanded the branch of quantum physics, overcoming problems faced by classical physicists and paving the way for modern physics.

Graph of the photoelectric effect



Electrons ejected from the metal surface due to photoelectric effect are called photoelectrons. Differing metals hold electrons with different forces. If the incident EM radiation illuminating the metal surface is of sufficiently high frequency to overcome the energy holding the electrons in the metal, electrons will be emitted.

If the graph of the maximum kinetic energy of the emitted electrons (eV) is plotted versus frequency of the incident light, the gradient representing each line is the same - Planck's constant.

The threshold frequency (f_0) is such that monochromatic light with lower frequency than this will not produce photoelectric effect with that metal, but electrons will be ejected if the frequency is higher than f_0. This is represented as the x-intercept.

The work function is the minimum energy required to remove the electron from the metal surface, represented as the y-intercept.

Overall, the equation for this is: $E_{k\,max} = hf - W$

Where $E_{k\,max}$ = max kinetic energy of an emitted electron, W is the work function, h*f* is the energy of the incident photon.

Note that $W = hf_0$. Therefore, $E_{k\,max} = hf - hf_0$. [if energy of incident photon is above the work function, photoelectrons are emitted from the surface with E_k equal to the difference between photon energy and work function.

To find velocity of photoelectrons: (1/2) $mv^2 = E_{k\ max} = hf - hf_0$.

If work y-axis is in volts, to convert: V=W/q, therefore, W = Vq, where V is from the graph and q is -1.6×10^{-19}J for a single electron. And then 1eV = 1.602×10^{-19}J, therefore, W = Vq/1.602×10^{-19} = V. Except now the units are in eV.

identify data sources, gather, process and present information to summarise the use of the photoelectric effect in photocells

A p-n junction is formed when joining a p-type and n-type semiconductor. The term junction refers to the boundary interface where the two regions of semi-conductor meet.

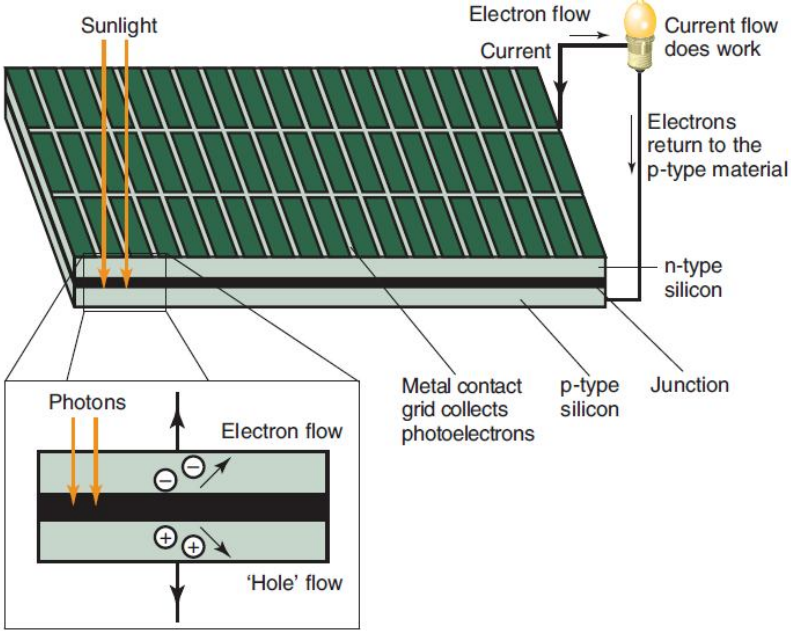
Use of photovoltaic cells in rural communities

Light meters used extensively in photography and cinematography. Many modern cameras have built-in meters.

A photomultiplier tube ranges in application, including: nuclear and particle physics, anatomy, medical diagnosis, blood tests

A photocell is a device using the photoelectric effect, i.e. photovoltaic cells, photoconductive cells and phototubes.

Photovoltaic cells convert energy from sunlight into electrical energy. Light energy is applied to the p-n junction region of the semiconductor diode. Electrons are released from the silicon crystal lattice due to the photoelectric effect, having the effect of raising the junction voltage. Since the n-type layer is exposed to the light awhile the p-type layer is not, photoelectrons are emitted from the light exposed n-type silicon surface. On the light exposed side of the solar cell, a fine grid of metal acts as electrical contacts, collecting the emitted photoelectrons.



Photoconductive cells (or photo-resistor), is made of high resistance semi-conductor material. Light shining on the material releases electrons from the lattice structure into the conduction band (via photoelectric effect). Additional light released can dramatically reduce resistance of the material (i.e. CdS, PbS & PbTe).

These materials are sensitive and photoconductive to different parts of the EM spectrum and can be used as light sensitive switches for street lights, light gates and counting devices.

Light meters also employ photoconductive cells, using the photoelectric effect and a galvanometer to measure the amount of light present. An increase in light intensity, increases the number of photons and hence the amount of photoelectrons. This registers a reading on the galvanometer which can be interpreted as light intensity.

Phototubes, (or photocells) also work according to the photoelectric effect, and are commonly used as detectors for opening automatic doors in shopping centres or turn taps on and off in toilets.

In astronomy, these can be used to measure EM radiation from stars or galaxies.

Photomultiplier cells are a type of phototube, using the effect of secondary emission to multiply the number of electrons released by a factor of a million. They are extremely sensitive, high gain, low noise detectors essential in

physics,
anatomy,
medical diagnosis,
blood tests,
medical imaging,
and astronomy.

Photomultiplier cells are a type of phototube, using the effect of secondary emission to multiply the number of electrons released by a factor of a million. They are extremely sensitive, high gain, low noise detectors essential in nuclear and particle physics and other areas.

- process information to discuss Einstein's and Planck's differing views about whether science research is removed from social and political forces

Planck and Einstein had different views towards the role of science research in supporting social and political forces.

Two groups in the scientific community emerged. In one group was Planck, a patriotic strongly supporting the German government. He believed that scientific research assisting the government was justified, signing the manifesto of the 93 intellectuals- a declaration supporting the acts of German army.

In contrast, Einstein found the application of science to the war effort troubling and signed an anti-war counter-manifesto as he was a pacifist, advocating peace. Being a humanitarian, he supported science as a human endeavour for the pursuit of knowledge and understanding the world around us, rather than for the purpose of supporting political forces.

At a young age, he avoided social and political persecution as he lived in Switzerland and now publically promoted the idea that scientific research should not have a political agenda.

Although Planck supported whatever government was in charge, he feared that science would become an instrument possibly abused by those in charge if the leaders were dictators and militarists.

His fears came true with Hitler coming to power. However, he ignored these political factors as he compromised to "work within the system". But eventually, he regretted signing the Manifesto and openly opposed Nazi anti-Semitism, intervening on behalf of Jewish scientists and praised Einstein.

He saw the socially moral imperative of opposing Hitler and in 1933 he tried to convince Hitler to stop. So these social and political factors ultimately affected his scientific research and he resigned from presidency of the Kaiser Wilhelm Institute in 1937.

Einstein emigrated from Germany and tried kept his research pure as he supported no governments. However, despite his pacifist ideals and belief that research should be removed from social and political forces, ultimately he urged the US to develop a nuclear bomb before Germany. He was influenced by political factors as he didn't want the disastrous social aspects of Germany winning the war. Furthermore, Nazi atrocities presented social factors that prompted him to aid in the Manhattan project. He wrote of pain and regret when the bombs were finally used.

3. Limitations of past technologies and increased research into the structure of the atom resulted in the invention of transistors

- identify that some electrons in solids are shared between atoms and move freely

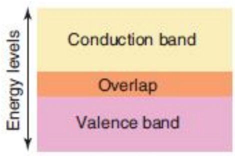
Some electrons are loosely bound and move freely as they are shared between the atoms. As the electrons move across the entirety of the solid, such solids can conduct electricity.

These are known as conductors, which are generally metals, where the outermost valence electrons are not attached to a particular atom. Instead, atoms form an ionic lattice and delocalised valence electrons move randomly in a cloud of negative charge. Under the influence of an electric field, the random motion of electrons decrease, and begins to have a net motion in a direction opposite to the electric field. This net motion produces the electric current.

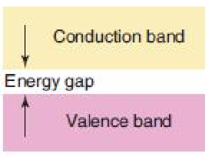
However, in insulators, electrons are shared between atoms via strong covalent bonds, and electrons are held tightly. Since electrons aren't free to move, they are poor conductors. Typically, a ionic compound forms when a metal atom donates an electron to the non-metal atom, forming a negative and positive ion, both with complete outer-valence shells. I.e. solid NaCl

Although held together by electrostatic forces when solid, ionic compounds can still conduct electricity in a molten state.

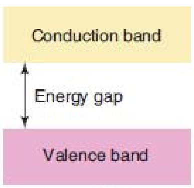
- describe the difference between conductors, insulators and semiconductors in terms of band structures and relative electrical resistance



(a) Conductor



(b) Semiconductor



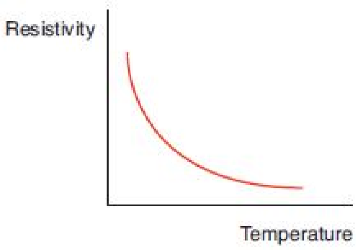
(c) Insulator

Electrons occupy atomic orbitals of defined energy in an atom. There exists band gaps, which are sections of energy level in which no orbital energy level exists (forbidden energy levels).

- The valance band is the highest energy level occupied by electrons that are not free to move to conduct electricity.
- The conduction band is the energy level occupied by an electron able to move freely to conduct electricity.
- The forbidden (energy) gap cannot be occupied by electrons and consists of the energy values that lie between valence and conduction bands.

Conductors, insulators and semiconductors differ in the size of the energy gap.

- Conductors have overlapping valence and conduction bands so valence electrons occupy the higher energy unfilled levels of the conduction band.
  - Thus conductors have relatively low electrical resistance.
  - *Noting that most conductors are metals, which increases electrical resistivity due to increase in temperature.*
- Insulators have a large energy gap and it is very difficult for electrons to move into the conduction band.
  - Thus insulators have high electrical resistance.



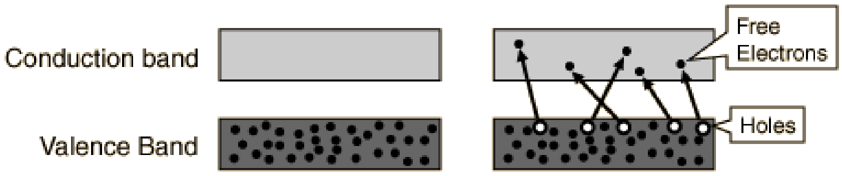
- Semiconductors have a small forbidden energy gap. Sufficient energy from external heart or light allows electrons in the valence band to enter the conduction band.
  - Thus, semiconductors have resistivity which decrease markedly with increasing temperature.

	Insulators	Semi-conductors	Conductors
Valence Band	Fully occupied	At absolute zero, full. At higher temperatures, partially occupied.	Valance and conduction bands overlap, electrons are free to move between them.
Conduction	Empty	Empty at absolute zero,	Overlapping

Band		partially occupied at higher temperatures	
Forbidden Gap	Very large	Small	None
Relative resistance	High as a lot of energy is required for valence electrons to jump to the conduction band	Low, so if valence electrons are supplied with sufficient energy, they may jump to the conduction band.	Very low, overlapping conduction and valence bands overlap and valence electrons jump easily to the conduction band, conducting electricity.

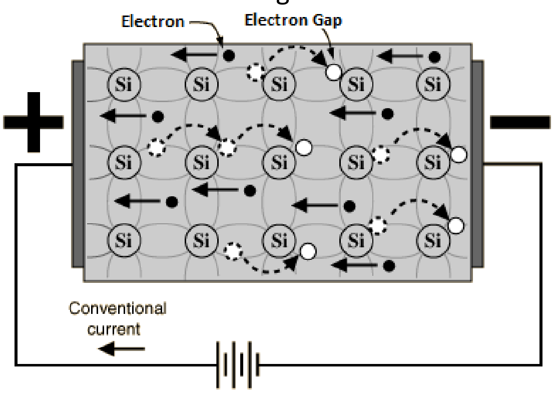
identify absences of electrons in a nearly full band as holes, and recognise that both electrons and holes help to carry current

For semi-conductors, its valance band is completely full at absolute zero. However, if sufficient energy is supplied by external light or heat, valance electrons will become excited and move into the conduction band. The number of electrons in the conduction band increases as temperature increases.



Absences of electrons in a nearly full band are holes. These gaps are created as electrons move out of the valance band. Both electrons and holes help to carry current. When an electric field is applied:

- Free electrons in the conduction band moves towards the positive terminal.
- Valance electrons also move towards the positive terminal, jumping to fill a hole in the neighbouring atom, subsequently creating a hole in their original position. Holes act as positive charge carriers, moving in the opposite direction towards the negative terminal.



perform an investigation to model the behaviour of semiconductors, including the creation of a hole or positive charge on the atom that has lost the electron and the movement of electrons and holes in opposite directions when an electric field is applied across the semiconductor

The model is a queue of patients waiting to see the doctor. Empty seats represent holes in atoms, while patients sitting in the chairs act as electrons. The queue is a part of a predefined path around the classroom, representing the semiconductor connected to an external circuit.

The patients' motivation to see the doctor at the front of the queue acts as the voltage applied across the semiconductor. When the doctor dismisses a patient (electron), the patient leaves an empty seat and walks around the classroom, i.e. creating a hole and entering the external circuit.

The rest of the patients move up the queue due to their motivation to see the doctor (electric field), and the movement of the patients (electrons) results in the empty seat (hole) moving in the opposite direction.

Meanwhile, the last dismissed patient has (electron) walked around the classroom (circuit), and returns in time for another patient (electron) to be sent off into the classroom (circuit). The process is repeated, demonstrating the creation of a hole, and the movement of electrons and holes in the opposite direction when an electric field is applied.

However, this model faces limitations:

- It represents electrons and holes, but doesn't represent semiconductor atoms themselves.
- It also represents the semiconductor as a 2d line and not a 3d lattice. Also it acts on the assumption that there is one electron to one hole and they all participates in the movement, whereas in reality, there would be many more valence electrons present than holes, and only some will move to fill the holes.

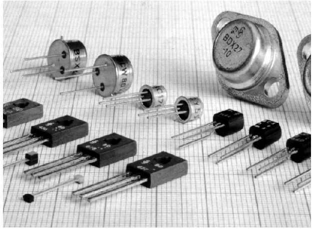
■ compare qualitatively the relative number of free electrons that can drift from atom to atom in conductors, semiconductors and insulators

The number of free electrons drifting from atom to atom differs due to nature of the material:

- Conductors have many free electrons, these electrons occupy the conduction band.
- Semi-conductors have no electrons in the conduction band at absolute zero. Though as temperature increases due to input of external heat or light energy, electrons occupy the conduction band. Hence the number of free electrons increase as temperature increases.
- Insulators have very few, but usually no electrons in the conduction band. Therefore there are very little or no free electrons.

Material	Type	Resistivity (Ωm)
Aluminium	Metallic Conductor	2.5×10^{-8}
Copper	Metallic Conductor	1.6×10^{-8}
Germanium	Semi-metal Semiconductor	0.9
Silicon	Semi-metal Semiconductor	2000
Glass	Non-metallic insulator	10^{10}-10^{14}
Wax	Non-metallic insulator	10^{12}-10^{17}

■ identify that the use of germanium in early transistors is related to lack of ability to produce other materials of suitable purity



Semiconductors used in electrical applications required ultrapure materials otherwise semiconducting properties are compromised. In the 1950s, sufficiently pure germanium was easier and cheaper to produce than sufficiently pure silicon. <see left top>

Later, widespread adoption of silicon ensued as technology allowed silicon of suitable purity to be produced. Silicon transistors <left bottom> has many advantages over geranium as:

- It is much more abundant (i.e. SiO_2 in sand), hence raw materials are cheaper.
- While germanium allowed too much current to pass through at high temperatures and caused damage to circuits, silicon maintained semi-conducting properties at high temperatures.
- It can carry a higher current for longer periods of time compared to germanium.
- Silicon forms an oxide which can be doped and formed into thin layers.

Hence germanium was used for semiconductors in early devices due to inability to produce silicon to a suitable purity.

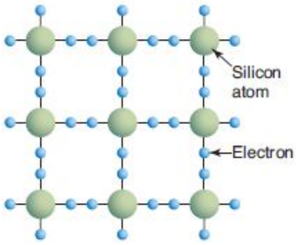
■ describe how 'doping' a semiconductor can change its electrical properties

Geranium and silicon are group 4 semi-metals with 4 electrons in the valence shell. Without any impurities, they are intrinsic (pure) semiconductors.

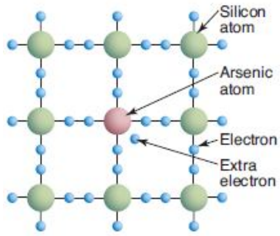
Doping is a method of enhancing conductivity of a semiconductor by the addition of specific impurities. Hence they become extrinsic semi-conductors whose properties are mainly characterised by the additive.

N-type semiconductors are formed when a Group 5 impurity atom which has five valence electrons (i.e. phosphorous or arsenic), is added to a semiconductor via doping. Only four electrons are required to bond with silicon atoms of the host semi-conductor, and the fifth electron is loosely bound, requiring very little energy to free it from the dopant into the conduction band. Hence, this dopant is an electron donor, increases the number of free electrons (negative charge carriers).

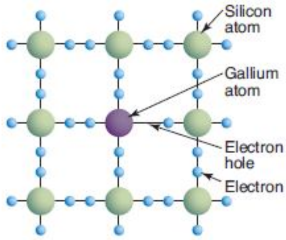
P-type semiconductors are formed when a Group 3 impurity atom which has 3 valence electrons (i.e. boron, gallium) is added via doping. Since four electrons are required to bond with silicon atoms of the host semi-conductor, electrons from valence shells of neighbouring atoms can jump into the relatively positive hole. The movement of this hole through the semiconductor represents the flow of positive current. Hence this dopant is an acceptor of electrons.



Lattice structure of silicon



Lattice structure of a: N-type semiconductor Silicon doped with arsenic



Lattice structure of a: P-type semiconductor Silicon doped with gallium

■ identify differences in p and n-type semiconductors in terms of the relative number of negative charge carriers and positive holes

A n-type semiconductor is formed when a semiconductor is doped with a Group 5 impurity atom with 5 valence electrons. The dopant is an electron donor.

Whereas a p-type semiconductor is formed when a semiconductor is doped with a group 3 impurity atom with 3 valence electrons. The dopant is an electron acceptor.

	Charge carrier	Dopant	Energy Band
n-type semiconductor	Conductivity due to negative charge carriers (electrons)	Group 5 element with 5 valence electrons are used (pentavalent)	Donor level created under conduction band.
p-type semiconductor	Conductivity produced by positive holes	Group 3 elements with 3 valence electrons are used as dopants (trivalent)	Acceptor level created above valence band.

In both cases, the doping results in a smaller forbidden energy gap.

■ gather, process and present secondary information to discuss how shortcomings in available communication technology lead to an increased knowledge of the properties of materials with particular reference to the invention of the transistor

Also relate to WWII.

In the mid 20th century, communication technologies such as radios and black and white TVs used thermionic devices (valves). It was apparent that they had many shortcomings as they:

- Were physically bulky
- Consumed a lot of power for consumption
- Had fragile glass valves susceptible to burning out. They had high failure rates and limited lifetime.
- Had limited response times.

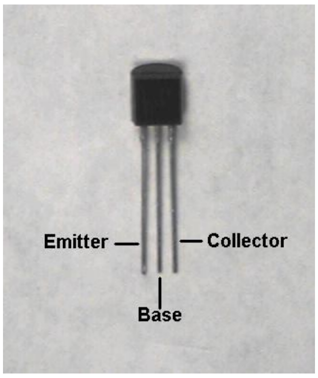
Scientists researched materials and their applications to replace thermionic valves used in appliances and communication devices. Extensive research into materials first used germanium's semi-conducting properties in transistors. They were used instead of silicon because of the inability to produce silicon to a suitable purity due to lack of technology. Transistors made of germanium replaced use of valves as they were:

- Compact
- Power efficient
- Mechanically rugged
- Able to operate at high switching speeds

However, Germanium transistors faced certain limitations, such as the raw material being rare and at high temperatures it allows too much current to pass, damaging the circuit.

With better technology, germanium transistors were phased out as silicon ones were made, which had many advantages over germanium. Doping of transistors also increased their versatility and scope of applications.

describe differences between solid state and thermionic devices and discuss why solid state devices replaced thermionic devices



Thermionic devices (i.e. valves) rely on thermionic emission of electrons from a cathode to an anode to control the direction of current flow. The heated cathode filament emits electrons which are accelerated by the high potential difference. The filament and anode terminal are set inside glass vacuum tubes which are fragile, bulky and can leak.

However, solid state devices such as transistors and integrated circuits are made of semiconductor material and controls the direction of current flow. Though its purpose in a circuit is the same as a valve, there is no need for an anode plate or cathode filament and can operate at standard room pressure without vacuum. Hence its construction is sturdier.

Both devices serve to:

- Rectify - convert AC to DC, allowing current flow in one direction
- Amplify - convert low voltage/current signal to higher voltage/current
- Switch - Control the particular part of a circuit voltage is applied.

Thermionic devices is slow and needs a heat supply for thermionic emission. Hence, it requires a separated heating circuit, and large amount of heat is produced, requiring cooling systems and special air conditioned rooms. Build up of heat risks damage of adjacent components.

Whereas, solid state devices can operate at room temperatures with no need to warm up and are 100000 times faster than thermionic devices, producing only small amount of heat.

Finally, solid state devices are more economical to produce since many identical integrated circuits can be made and cut up during mass production.

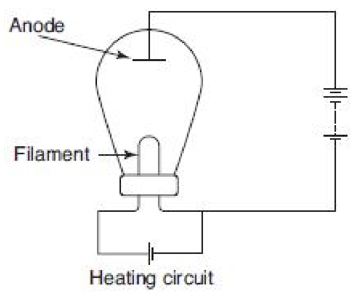
Solid state devices have replaced thermionic devices in many applications due to:

- Increased reliability
- More economical - lower power requirements, easier to produce
- Relatively compact and sturdier
- Doesn't require warm up, so it operates faster
- Not made of fragile glass like valves.

Thermionic Devices in detail

A thermionic valve utilises heated filaments and terminals set inside a glass vacuum tube. The filament in vacuum acts as a cathode as it is heated, causing electrons to be liberated and accelerated by high potential difference towards the anode.

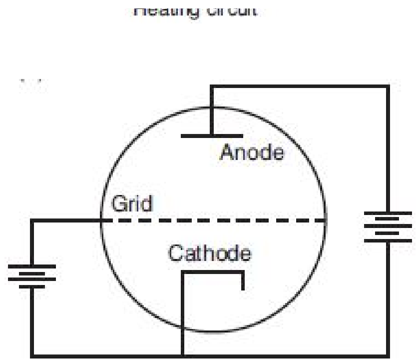
Diode



The simplest valve is a diode, with two elements inside the glass vacuum tube: a cathode an a anode plate. The cathode is heated directly (with current) or indirectly (with a separate heating filament) with the negative terminal attached to the cathode. Electrons flow through the diode and no current will flow if the battery is connected in reverse.

This allows for unidirectional conduction suitable for an electronic switch, and for converting AC to DC (rectification)

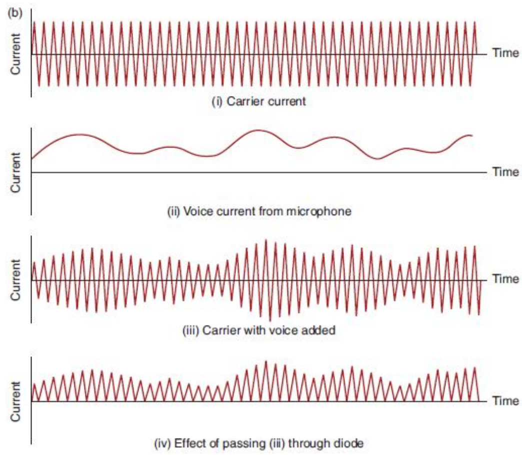
This allows for unidirectional conduction suitable for an electronic switch, and for converting AC to DC (rectification).



Triode

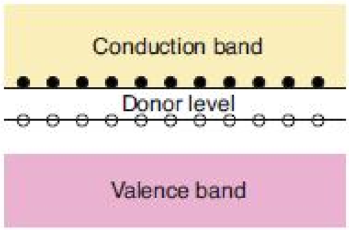
The triode is just like a diode, except there is a third electrode in the vacuum diode called the grid placed closer to the cathode than the anode. The grid circuit is adjusted separately from the anode circuit and voltage placed on the grid has a much larger effect on the electric field within the valve. Hence, the grid can be used to control the anode current and the triode can act as a current amplifier.

When an alternating voltage or signal is applied to the grid, the electron current is an amplified replica of the signal voltage. With a high voltage applied between the cathode and anode, small variations in grid current produced amplified signals in the anode circuit.

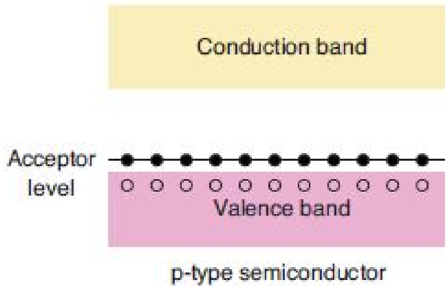


Solid State Devices

Solid state transistors and integrated circuits are made from semi-conductor materials.



Energy band changes in a doped n-type semiconductor. The level is called donor because electrons are donated to the conduction band.



Energy band changes in a doped p-type semi-conductor. The level is called acceptor because electrons are accepted from the conduction band.

Diode

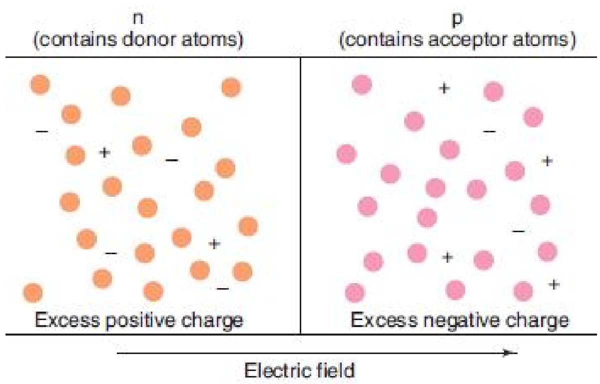
A junction or interface between a p-type and n-type semiconductor acts as a diode. Dominant charge carriers of n-type and p-type semi-conducting material are electrons and holes respectively.

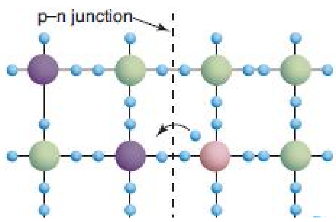
These mobile charge carriers will diffuse from one type of material into the other.

- Electrons moving from n-type to p-type material will introduce negative charge to the p-type material and leave the n-type material positively charged.
- While holes moving from p-type to the n-type material, introducing positive charge to the n-type and leaving the p-type negatively charged.

This only allows electrons to flow in one direction from the n-type to neutralise available holes in the p-type semiconductor material.

The overall effect is the build up of positive

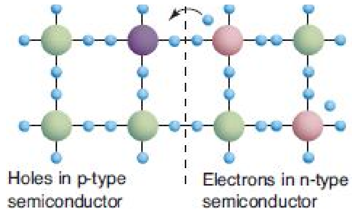




from the n-type to neutralise available holes in the p-type semiconductor material.

The overall effect is the build up of positive charge on the n-type material, and negative charge on the p-type. Hence an electric field is established across the depletion zone across which the charge carriers diffuse. This electric field increases until it opposes further diffusion of charge carriers across the interface.

Presence of this electric field can be used to explain the diode nature of the p-n junction.

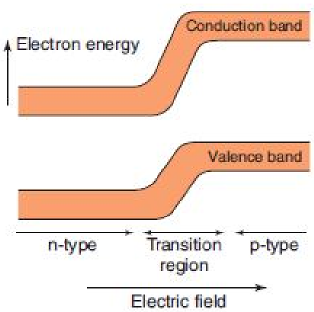


Hence conventional electrical current is confined to one direction:

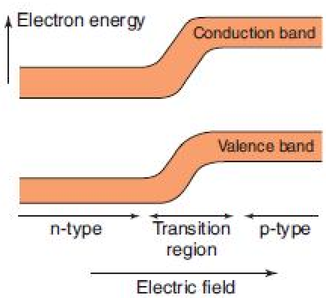
- From the positive terminal of the battery
- Into the p-type semiconductor
- Out of the n-type semiconductor
- To the negative terminal of the battery.

So when positive potential is applied to the p-type and negative potential applied to the n-type material, the diode is connected in such a way to have a **forward bias** applied to it. Hence, the energy difference between the valence and conduction bands is decreased and a large number of electrons can flow from the n-type to the p-type, as a corresponding number of holes flow in the opposite direction.

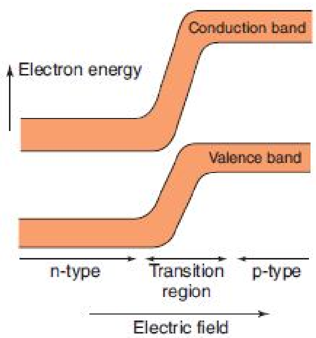
If connected the other way, with the positive potential applied to the n-type material and negative potential to the p-type material, the diode acts as a large resister with **reverse bias**. No current, or very minute current can flow through the diode as electrons can't pass from n-type to p-type, while holes can't pass from p-type to n-type. This is due to the increase in energy difference between the valence and conduction bands.



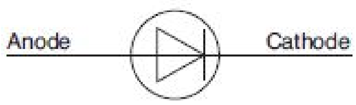
Energies of valence and conduction bands when junction at thermal equilibrium.

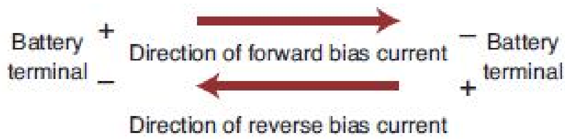


Forward bias voltage is applied.



Reverse bias voltage is applied

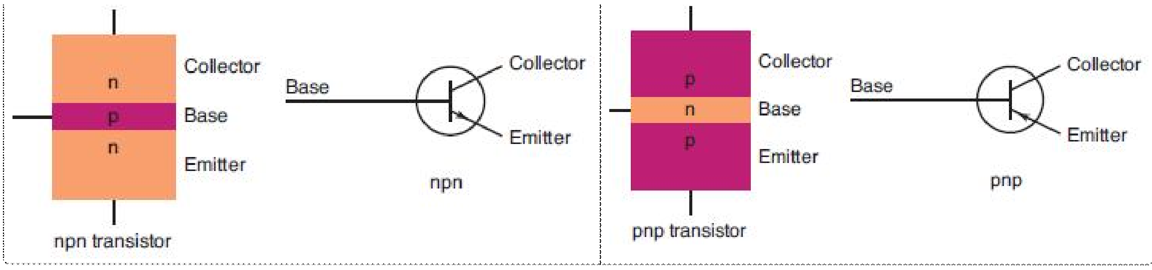




The arrow on this diode indicates the conventional current flow possible through it. Note it is unidirectional.

Transistor

Invented at Bell Laboratories, it was observed that when electrical contacts were applied to a geranium crystal, the output power was larger than the input. Transistors are solid state semiconductor devices used as a switch or a part of an amplifier. There are two types: NPN and PNP transistors.

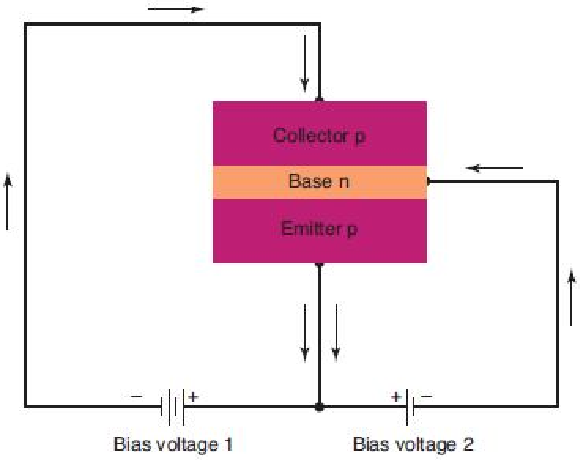


Transistors are simply a combination of two junctions. In PNP transistors, it consists of a thin layer of n-type material between two sections of p-type material. NPN transistors, it's reversed.

The three connections are called the emitter, base and collector and each junction must be correctly biased for the transistor to function.

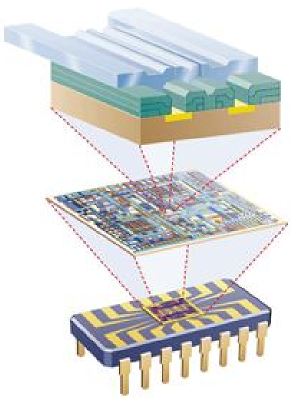
For a PNP transistor, mobile electrons in the n-region initially move towards the positive terminals while the holes move towards the negative terminals.

Holes move across the forward biased junction from the p-type emitter into the n-type base. Most of these holes don't recombine with electrons in the base, but flow across the second junction into the collector.



This arrangement is an amplifier as small changes in the voltage of the base, causes large changes in the voltage drop across the collector's resistance. This is because the input impedance (electrical resistance) between the emitter and base is low, and the output impedance is high.

- identify data sources, gather, process, analyse information and use available evidence to assess the impact of the invention of transistors on society with particular reference to their use in microchips and microprocessors



Replacing valves, transistors were enormously smaller at around 1cm. These components saw big improvements in reliability and are wired into circuit boards. Soon, portable radios were reduced from the size of a briefcase to a small book and by the 1960s, transistors almost completely replaced valves.

Integrated circuits were invented by the mid 60's, which was a complex circuit built up in layers on a single crystal of silicon with around ten components. By 1970, a thousand components were used, and today, circuits have millions of components on a cm^2 of silicon. Their advantage is that soldering and wiring were eliminated and interconnections are built into the chip, eliminating wiring and soldering thus increasing reliability and speed.

Since the first microprocessor in 1971, many household appliances have them today. Computers have reduced from room sized machines to laptops today which are much more powerful.

It has revolutionised communication, being faster and cheaper due to email, mobile phones, etc. Credit transactions via EFTPOS and ATM are now possible, although electronic transactions instead of manual labour have employment implications. Similarly, many manual jobs have been replaced by automation made possible by computing, and decreased jobs. However, new industries and areas such as IT and internet related companies have provided more employment.

Personally, there are more leisure activities with electronic devices. However, this comes at the cost of less interpersonal interaction and a potentially

employment.

Personally, there are more leisure activities with electronic devices. However, this comes at the cost of less interpersonal interaction and a potentially sedentary lifestyle, having long term health implications.

Productivity increases with programs such as word processing has made a big difference to education and the workplace.

However, individual privacy has become an issue with electronic surveillance made possible.

Top left - Microchip (the latest have more than 2 billion transistors)
Left - Microprocessor in a PC (more than 700million transistors).

- identify data sources, gather, process and present information to summarise the effect of light on semiconductors in solar cells

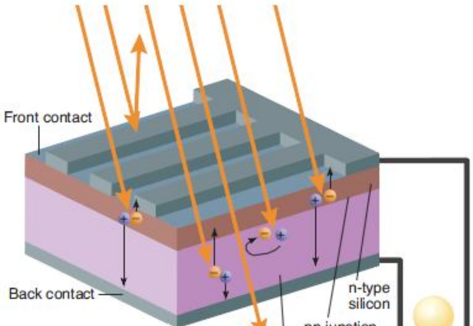


Figure 12.26 *Principal structure of a crystalline solar cell*

An application of semiconductors is in photovoltaic cells or solar cells. Its operation is based on the natural potential difference of the formed p-n junction, which permits current flow from the p to the n side. [noting that conventional current is from the positive to the negative terminal through the circuit].

Solar cells comprise of discs or wafers of crystalline silicon which are grinded and cleaned before doping, metallisation, and being coated with anti-reflective material. The n-type silicon is joined on top of the p-type silicon in the resulting cell, creating a p-n junction.

Initially, the p- and n-type silicon wafers are neutral, but free electrons in the n-side to move across the junction into the free holes on the p-side. As electrons fill the holes, a level of equilibrium is eventually reached in terms of charge distribution about the junction. This field acts as a diode, allowing electron flow from the p-side to the n-side, but not in reverse.

When some light striking the cell is absorbed, light photons transfer energy to the semi-conductor as they knock electrons from the valence to the conduction band, freeing electron-hole pairs. A photon with more than the minimum energy level frees exactly one electron, and produces a hole. The electric field sends electrons to the n-side while holes migrates to the p-side.

A one way current is maintained by placing metal contacts at the top and bottom of the solar cell. Electrons collected by the metal plate on the n-type side of the PV cell is fed back to the p-type side of the PV cell to fill holes as the metal plates are connected by external circuit. Hence, the potential difference between the p and n type sides causes electron flow in the external circuit, producing current which can be used to do work, i.e. power calculators, telephones, etc.

Energy loss is minimised by covering the PV cell with a metallic contact grid to shorten the distance electrons have to travel. The larger the grid, the more photons are blocked, but the smaller the grid, the higher the resistance; hence there's a trade off between grid size and current generation. Anti-reflective coating applied on top of the PV cell reduces reflection losses as reflected photons cannot be used for energy. Glass covering also offers protection.

Most PV cells are made composed of modules of many cells connected to increase both current (connected in parallel) and voltage (connecting in series), whilst adding terminals at the back.

The intensity of light (above the threshold frequency) falling on the photocell determines the size of photocurrent produced.

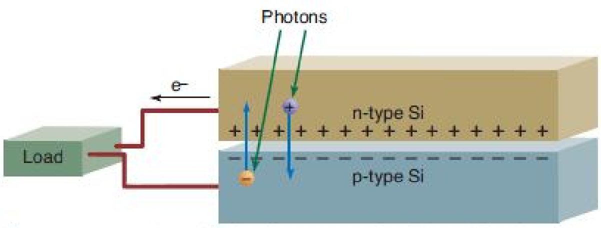


Figure 12.27 *Photons hitting electrons, causing them to be released from their structure and move in the diode, thus releasing energy to the load (which may, for example, be a calculator or a light)*

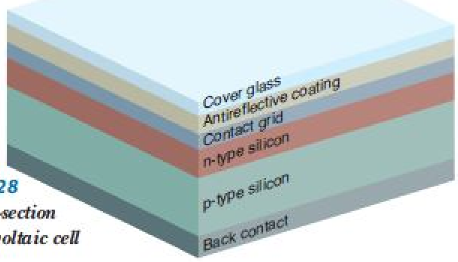


Figure 12.28 *Final cross-section of a photovoltaic cell*

4. Investigations into the electrical properties of particular metals at different temperatures led to the identification of superconductivity and the exploration of possible applications.

Our explanation of superconductors depends on our understanding of the crystalline structure of conductors made possible by x-ray diffraction.

Recap

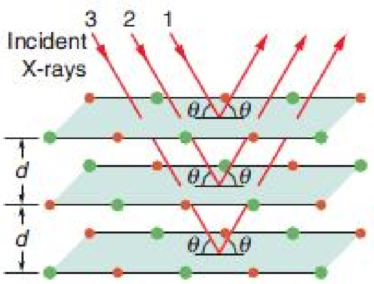
When two waves combine in an effect called superposition, the amplitude of the resultant wave at every point is found by adding the displacement of each wave. Waves can interfere with each other constructively, making waves of larger amplitude, or destructively where the resulting wave amplitude is zero.

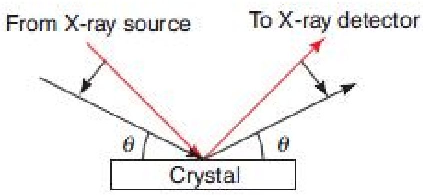
Complete constructive interference occurs when waves from two points arrive at the same point with the same phase. Since waves are continuous, constructive interference will occur as long as they are a whole number of wavelengths apart and hence it's still in phase. i.e. $\Delta D = n\lambda$.

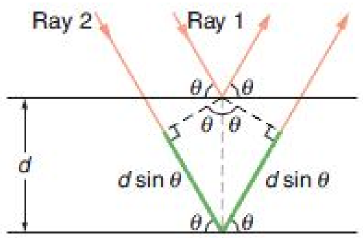
When light from a single monochromatic source is passed through a double slit in a diffraction grating, the coherent waves interfere. Bright areas on the screen are points of constructive interference, while dark spots are minima and points of destructive interference.

In young's double sit experiment, we see that light doesn't travel past objects in a straight line, but spreads out around the object's edges as waves, which also occurs when light passes through a small aperture. This spreading out of light is known as diffraction and more pronounced areas are where differences in path length approach multiples of half or full wavelengths.

- outline the methods used by the Braggs to determine crystal structure



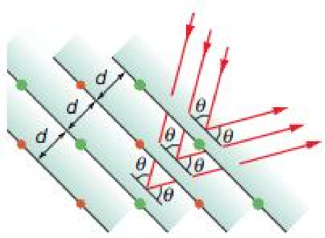




It was proposed that a crystal could act as a 3d diffraction grating for x-rays as x-rays have wavelengths similar to the gap between atoms in the crystal lattice (10^{-10}m). Since the precise nature of diffraction is dependent on the geometry of the object causing it, the structure of the crystal could be determined by the process of x-ray diffraction. Sir William and Lawrence Braggs developed an x-ray spectrometer to systematically study the diffraction.

A 40kV x-ray tube produces x-rays when cathode rays hit a metal anode. The x-rays were collimated by parallel plates molybdenum coated metal. This parallel x-ray beam is directed at a metal salt, and atoms of the salt absorb and re-emit the x-rays, scattering in different directions. The Braggs used an ionisation chamber to detect the x-rays, (although photographic film can also be set around the sample, showing bright and dark spots where x-rays interfered constructively and destructively). This process of interference is related to the phase of each individual ray of x-ray. As the beams are collimated, they remain parallel upon reflecting from the regularly spaced, parallel planes of the crystal lattice. The angle ϴ of scattered x-rays can be determined by observing the interference pattern in a detector (i.e. photographic film).

A model of reflection rather than scattering is shown to simplify the process.



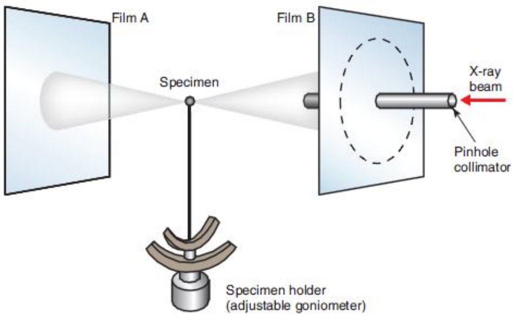
The Braggs utilised x-ray reflection from adjacent atomic planes to provide a mathematical interpretation of these experiments, deriving a relationship between the spacing of crystal planes, wavelength of radiation, and angle of reflection ϴ. Since, $\Delta D = n\lambda$.

$n\lambda = 2d \sin\theta$, where d is distance in angstroms, θ is diffraction angle in degrees, and n is a positive integer.

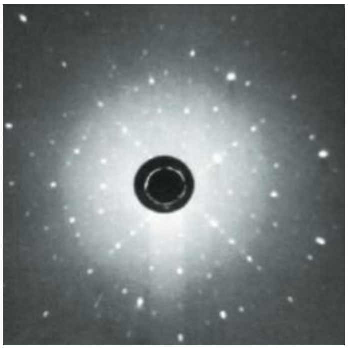
Hence, measurement of the angles allow spacing and arrangement of the crystal to be determined.

Hence, this method can be used to study spectra by placing a crystal with a known interplanar spacing. A detector is mounted on a goniometer and the crystal's rotation angles at which maxima occur is measured. A chart recorder produces a trace of x-ray intensity against rotation angle.

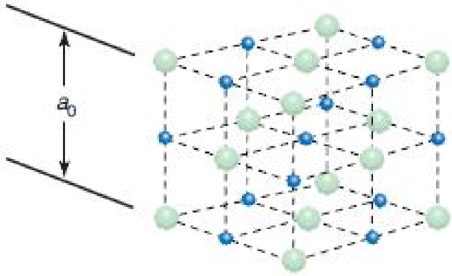
Conversely, a crystal can be studied with a monochromatic x-ray beam of known wavelength, determining spacing of crystal planes, and structure of crystal unit cell, (smallest possible crystal unit).



Flat plate camera for x-ray diffraction of a crystal



Pattern of silicon crystal

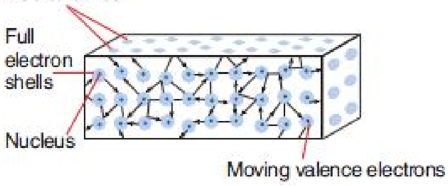


Smallest possible crystal unit (unit cell of sodium chloride).

- identify that metals possess a crystal lattice structure

Metals are considered crystalline in structure as it is uniform and not amorphous.

Metals are sometimes described as a 3d crystal lattice of positive ions are bonded together in a regular array. The metallic bonding is essentially an attraction between positive ions and a sea of delocalised electrons that continually drift through the crystal lattice.



Random motion of electrons in the metallic lattice.

- describe conduction in metals as a free movement of electrons unimpeded by the lattice

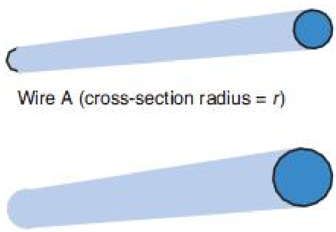
Without an electric field, the delocalised electrons exhibit random directions of movement, with equal numbers moving in each direction establishing a steady state. Therefore, there is no net transport of electric charge.

The application of an electric field produces a small component of velocity in the direction opposite to the direction of the electric field. This movement of electrons through the lattice conducts electricity in metals, and the velocity of the electrons is proportional to the strength of the electric field.

- identify that resistance in metals is increased by the presence of impurities and scattering of electrons by lattice vibrations

Resistance in metals is affected by a variety of factors:

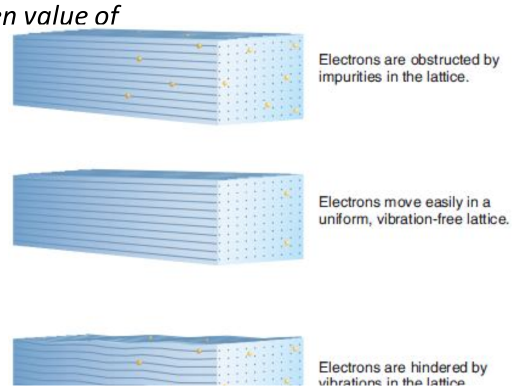
- Length - longer = more resistance
- Conductor type
- *DC and low frequency AC travel through the body of the metal, and the greater the **cross sectional area**, the more electrons and hence current can flow along a wire for a given value of voltage.*



As electrons move, they can **collide** with vibrating lattice ions and impurities in the lattice. Hence, the electrons loses energy and some of its velocity, disrupting the flow of current. This causes scattering of electrons and increases resistance.

Furthermore, atoms of the metallic lattice also **vibrates** more with increasing temperature, further increasing resistance.

Presence of these irregularities in the conductor obstructs electron movement and increase the resistance of the metal.



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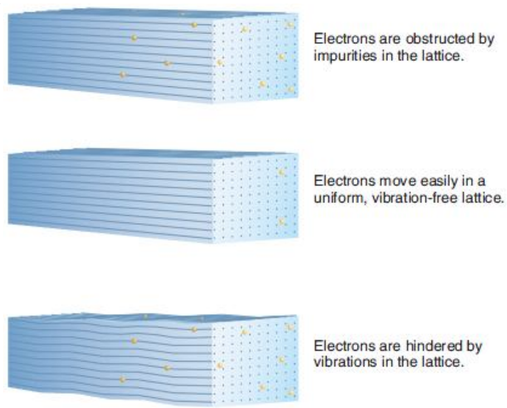
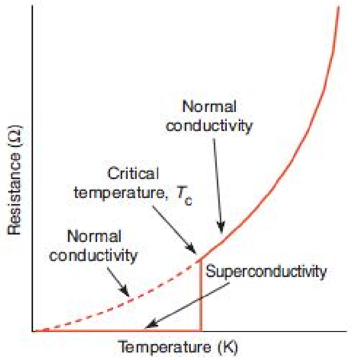
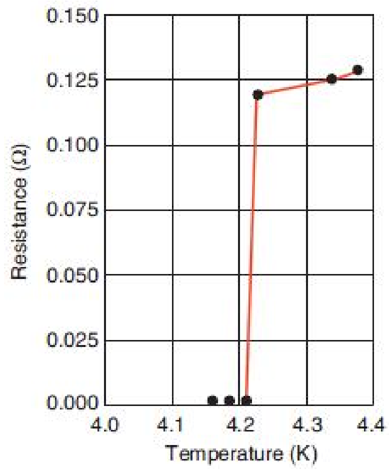


- describe the occurrence in superconductors below their critical temperature of a population of electron pairs unaffected by electrical resistance



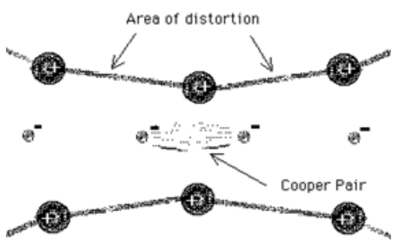
Superconductivity is the phenomenon in which a conductor cooled sufficiently past a critical temperature T_c, exhibits negligible resistance. Unlike normal conductors, superconductors below T_c allow electrons pass almost unobstructed through the lattice and avoid colliding with the impurities present. Hence, superconductors transmit electric current with no appreciable loss of energy.

This is based on formation of a population of Cooper pairs of electrons unaffected by electrical resistance.



- discuss the BCS theory

The theory is deeply founded on quantum mechanics, and classical explanations fail badly.



The basis for Type 1 superconductivity can be explained using the BCS theory, which explains traditional metallic superconductors (but not ceramic superconductors - type 2).

BCS theory showed that superconductivity occurred due to interaction between electrons such that they formed Cooper Pairs. Although electrons strongly repel each other, the mechanism producing the attraction between the Cooper pairs is phonons, i.e. packets of sound energy present in a solid due to lattice vibrations.

When a negatively charged electron travels past positively charged ions in the lattice, the lattice distorts inwards, causing phonons to be emitted forming a slightly enhanced positive charge just ahead of another electron. Before the electron passes through and the lattice reverts to its original position, the forces exerted by the phonons overcome the electrons' natural repulsion and a second electron is drawn to the first. The pair must have opposite spins so that they are not restricted by the Pauli exclusion principle. Furthermore, the pair has a considerable distance of separation such that the Coulomb repulsion doesn't completely dominate the attractive force.

Cooper pairs are coherent with one another as they passes through the conductor in unison without collision with the crystal lattice to reduce an electron's kinetic energy, hence having low resistance. Meanwhile, the Cooper pairs are constantly broken and reformed as the superconducting material carries an electric current.

Sometimes, phonons are exchanged between the pair, keeping the Cooper pairs together for longer and allows electrons to reach a lower energy state. There exists an energy gap that the electron must overcome to get out of the lower energy state. However, with reduced molecular motion at very low temperatures (below the critical temperature), the energy gap cannot be overcome by oscillating atoms in the lattice and maintains electrons in the superconducting state.

Hence, the BCS theory explained both microscopic and macroscopic properties of some superconductors, and predicted certain properties verified later including the Meissner effect.

Bardeen	Cooper	Schrieffer
Exchange of phonons between electrons allows an electron to reach a lower energy state. It must overcome an energy gap to get out of the state, hence the energy gap maintains the electron in the superconducting state.	Cooper that when electrons did interact, they did so in a pair (Cooper Pair). These pairs are constantly breaking and reforming and a key to superconductivity. There exists an attraction between the electrons due to phonons. The pair has a considerable distance of separation, and there would be an overlap of Cooper pairs (i.e. 10^6 or 10^7 in the same volume).	He applied statistical methods to solve difficulties in dealing with Cooper pairs mathematically.

- process information to identify some of the metals, metal alloys and compounds that have been identified as exhibiting the property of superconductivity and their critical temperatures

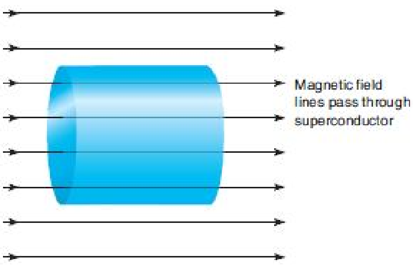
The critical temperatures of certain metals, alloys and metal oxide ceramics have been identified.

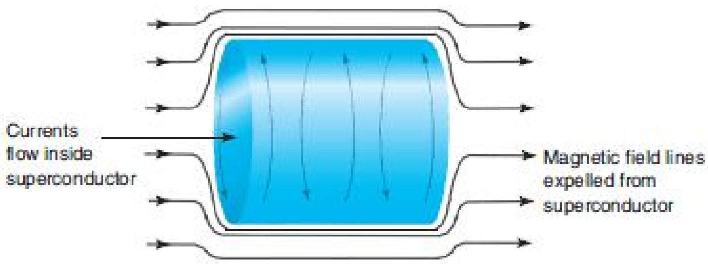
Generally, the critical temperatures of metals are low, alloys are higher while ceramics (type 2 superconductivity) have the highest critical temperature. Ceramics are complex metal oxides, and the superconductivity of these ceramics cannot be adequately explained using BCS theory.

ELEMENT/ALLOY	T_c (K)	T_c (°C)
Aluminium	1.20	−271.95
Hafnium	0.35	−272.8
Lead	7.22	−265.93
Mercury	4.12	−269.03
Niobium-aluminium-germanium alloy	21	−253.15
Technetium	11.2	−261.95
Tin	3.73	−269.42
Tin-niobium alloy	18	−255.15
Titanium	0.53	−272.62
Uranium	0.8	−272.35
Metal oxide ceramics		
$YBa_2Cu_3O_7$ (YBCO)	90	−183.15
$HgBa_2Ca_2Cu_3O_8$	133	−140.15

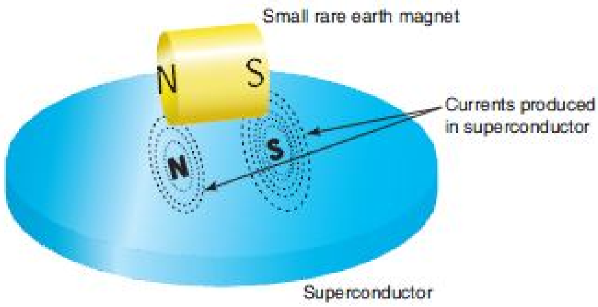
- analyse information to explain why a magnet is able to hover above a superconducting material that has reached the temperature at which it is superconducting

A magnet is able to hover above a superconducting material which has reached the critical temperature and is superconducting. This phenomenon is known as the Meissner effect, where a magnetic field is expelled from inside a magnetic field.





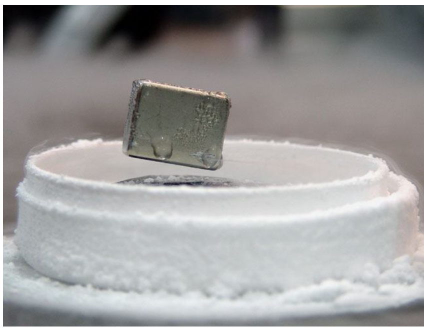
Above the critical temperature, magnetic field lines are able to pass through the superconductor, and magnetic field strength inside the material is similar to the outside. However, if the material is in its superconducting state, current flows in the superconductor arise and these have their own magnetic fields which cancel out the applied magnetic field inside the superconductor. Therefore, as magnetic fields are excluded, the net magnetic field inside the superconductor is zero.



If a magnet is brought near a superconductor, the currents in the superconductor that expel the magnetic field from inside a superconductor creates magnetic poles which repel the magnet with a repulsive force. So if a small magnet is placed above a superconductor, the repulsive force between the magnet and superconductor can balance the weight of the magnet, causing levitation.

Note that although levitation is due to repulsion, when the magnet is lifted, the superconductor can also be lifted with it. This attraction is due to some magnetic flux lines that managed to penetrate the superconductor and were trapped there by microscopic inhomogeneity. When the magnet is lifted up, the superconductor holds its magnetic lines and follows the magnet. The magnetic lines can be made to penetrate the superconductor by placing the magnet close to the superconductor at high temperatures prior to cooling, or pushing the magnet hard towards the cooled superconductor.

- perform an investigation to demonstrate magnetic levitation



Magnetic levitation of a small rare earth metal above a superconductor is possible through the Meissner effect. A Styrofoam cup is filled carefully with liquid nitrogen. A petri dish is placed on top of the Styrofoam cup and liquid nitrogen is poured in until it's about 1cm deep. After boiling subsides, use non-metallic, (non magnetic) tweezers to carefully place superconductor (YBCO) in the liquid nitrogen in the petri dish.

After boiling subsides, use same tweezers to place a small rare earth magnet 2mm above the centre of the superconductor pellet. Release the magnet. While the magnet is suspended, gently rotate the magnet using non-magnetic tweezers.

It was observed that the magnet is suspended above the superconductor magnet as the liquid nitrogen cooled the superconductor below its critical temperature. If the levitated magnet is gently rotated, the magnet continues to rotate.

- gather and process information to describe how superconductors and the effects of magnetic fields have been applied to develop a maglev train

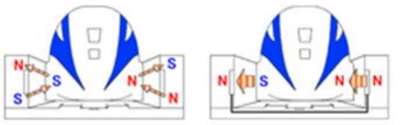
__EMS__ - less magnets than EDS, no need for cooling. But separation between vehicle and guideway must be monitored and maintained at 15mm.
__EDS__ - Allows heavier load capacity, is more stable. But requires cooling. Intense magnetic fields necessitate magnetic shielding to protect pacemakers, hard drives, etc. Guideway cannot lift train at low speeds, and

Maglev trains rely on the principle of magnetic levitation to suspend an object such that it is free of contact from any surface. This is useful for trains as it allows frictionless movement, resulting in quieter and faster operation.

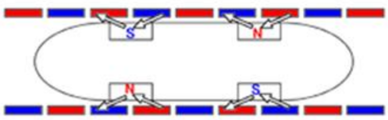
A maglev train is streamlined and travels along a guideway. There are two main types of maglev systems:

- EMS (in Germany) utilises conventional electromagnets mounted under the train on structures that wrap around the guideway. The attractive magnetic force between the magnet and rail lifts the train up. However this is dynamically unstable and needs to be monitored closely by computers with complex systems of feedback controls to maintain the train at 15mm from the track.
- EDS (in Japan) relies on the repulsive force between the superconducting magnets on the vehicle and electrically conductive strips/coils (electromagnets) in the guideway. This repulsive force arise from the

magnetic shielding to protect pacemakers, hard drives, etc. Guideway cannot lift train at low speeds, and requires an alternate system of wheels or landing gear to support the train until it reaches sufficient speed.

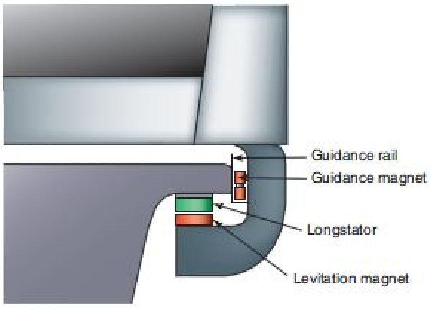


Levitation System   Guide System



Drive System

Electromagnetic Levitation



- EDS (in Japan) relies on the repulsive force between the superconducting magnets on the vehicle and electrically conductive strips/coils (electromagnets) in the guideway. This repulsive force arise from the Meissner effect and is naturally more stable than EMS and pushes the train away from the rail, levitating it. Although it doesn't require the same level of monitoring, the requirement for very low temperatures means that it is currently not a practical system.

In either case, since the train is very heavy, very powerful magnets are used. Once the train is levitated, continual change of the polarity of alternate magnets on the track results in a series of attractions and repulsions which provides a net force. This force overcomes air resistance and accelerates the train along the guideway.

Since air resistance is the only obstacle to higher speeds, speeds of 517kmh^{-1} has been achieved.

However, setting up the system requires a lot of new infrastructure, which is expensive. Further expenses arise from running such a system due to requirement for extremely large amounts of energy (and the need to cool superconducting magnets in EDS). Finally, very careful monitoring during its operation. These cost factors impedes its wider adoption.

- discuss the advantages of using superconductors and identify limitations to their use

Josephson Effect

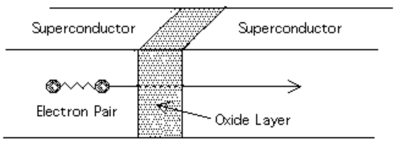


Fig. 13

A superconductor's property of zero resistance below its critical temperature is the biggest advantage when employing superconductors. This is useful in transformers, power storage, or power transmission where zero resistance means energy savings which would have been dissipated as heat energy in conventional systems.

Josephson junctions made of superconducting material is advantageous due to its ability to be a much faster switch than conventional materials. This can be employed in electronics, and particularly use in very sensitive equipment (e.g. magnetometers i.e. SQUIDs)

However, the main limitation of superconductors is the low critical temperature they require to attain zero resistance, and for metals, costly liquid helium must be used. Although high temperature ceramic materials can be used instead, they are too brittle to be shaped easily into useful materials (i.e. if used for long distance wires, cannot be overhead cable, must be a solid cable underground, but susceptible to earthquakes and tremors). These ceramic materials are also very expensive to produce.

Another limitation is their sensitivity to moving magnetic fields. I.e. conventional transformers use AC current, so for superconducting transformers, DC should be used instead and may require more research.

- process information to discuss possible applications of superconductivity and the effects of those applications on computers, generators and motors and transmission of electricity through power grids

Computing and Electronics

Currently, further miniaturisation of computer components (i.e. CPU) is limited by generation of heat due to resistance of current flow. Furthermore, the speed at which signals can be conducted is also limited and cannot be improved.

It was observed that two superconducting metals separated by an insulating layer will allow a tunnelling current to flow across this Josephson junction. But when a constant potential difference is applied, the current flow oscillates and allows the Josephson junction to act as a superfast switch. This can be applied in computing through the use of superconductive film (i.e. as connecting conductors) which can increase density of semiconductor chips, allowing transmission of information several orders of magnitudes faster than conventional switches.

Switching times of 9 picoseconds ($9x10^{-12}s$) has been achieved using superconducting electronic components. Using the same principle, very sensitive microwave detectors and magnetometers can be used for geological surveys.

Generators

Current conventional generators which utilise copper wiring and iron core have reached limits of their theoretical development potential. Superconducting magnets do not require an iron core and can be used to reduce the size and mass of generators by up to 70%. Furthermore, magnetic field can be maintained without need for a constant input of energy, and hence less fossil fuels is required to produce electricity, reducing greenhouse gas and other waste emissions from the power plant.

Motors

Superconducting motors are similar to AC synchronous motors, but differ as it employs high temperature superconductor (HTS) coils instead of conventional copper coils. Unlike copper coils, HTS coils can carry significantly larger currents and can generate a magnetic field of greater magnetic flux density.

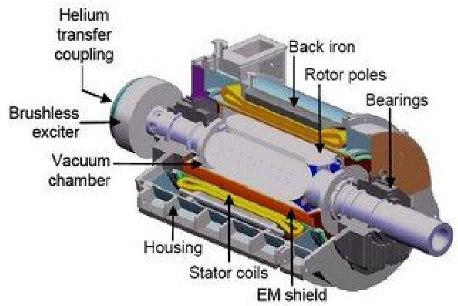


Figure 3: American Superconductor's 5 MW HTS marine propulsion motor

Motors with HTS coils are also comparatively smaller, being as little as one third the size and weight of a conventional motor of the same rating. Manufacturing costs of HTS coil motors are also less than equivalent conventional motors due to its compact nature, however cost of materials is higher. There is also potential energy savings as there's no need for constant input of energy, which reduce the cost of running the motor.

Note that since superconductors have no resistance, a small power supply can produce relatively large currents that lose no energy as they flow in the superconductor due to negligible heating effects.

This is ideal for producing intense magnetic fields (i.e. MRI/Maglev). High current is also ideal for motors, increasing their torque.

Electrical transmission

AC transmission through conventional wires dissipates 10-15% of generated electricity in resistive losses. Hence, there has been research into zero resistance superconductive transmission lines which conduct electricity without losing power. Fairly low voltage DC can be used instead of high voltage AC as constant current switching in AC causes energy losses and heating, defeating the purpose of thinner wires.

Since superconducting wires carry 3-5 times the current, hence relatively thin wires can conduct very large current densities. Current densities above 10,000 amperes per square centimetre are considered necessary for practical power applications.

A prototype line can transfer 1000MW of power within an enclosure diameter of 40cm. Hence, the entire output of a large power plant can be transmitted in one enclosed niobium-titanium transmission line.

However, physical limitations of brittle high-temperature superconductors must be overcome as well as developing an economically viable coolant system or a sufficiently high temperature superconductor (HTS) to reduce cooling costs. Currently, experimental HTS material is wound around a hollow core carrying liquid nitrogen coolant.