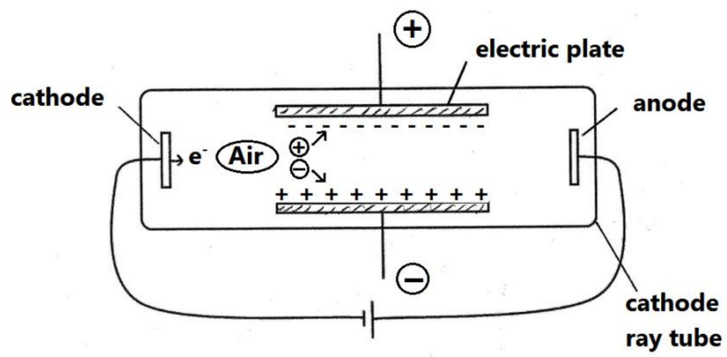
From Ideas to Implementation

3.1 Cathode Rays

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

- ***A cathode ray tube creates a vacuum environment and allows the manipulation of a stream of charged particles***.
- A cathode ray tube is a highly evacuated glass tube containing 2 electrodes.
- A high voltage applied across the electrodes causes cathode rays (streams of negatively charged particles) to accelerate from the cathode surface towards the anode.
- Structures built into or around the cathode ray tube allow the manipulation of a stream of charged particles.
  - Electric plates (electric field), magnetic coils (magnetic field) and extra anodes (e.g. collimators, which focus electrons into a thin stream) can change the path of the cathode ray.
  - Solid objects may be placed in the path of the rays to block them.
- Cathode rays are identical regardless of the material used.

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



- **Wave Properties**
  - Travelled in straight lines
  - Not deflected by electric fields (in early experiments)
  - Produced a shadow of an opaque object in its path
- **Particle Properties**
  - Turned a paddle wheel placed in its path
  - Travelled slower than light
  - Deflected by magnetic fields (and later, electric fields as well)
  - Emitted at 90° to cathode surface (not radiating like a wave)
- The major inconsistency in results was the deflection of the cathode rays by magnetic fields (suggesting they are charged particles) but the inability to deflect them with electric fields.
- The technology of that time did not allow cathode ray tubes to be evacuated to very low pressures.
- This meant that, once placed under high voltages, electrons would be ejected and accelerated towards the anode, but would quickly strike an air particle, ionising it. These ions will be attracted to oppositely charged electric plates, settling on their surface and eventually neutralising the electric field. The electrons are thus able to travel past the electric fields undeflected.

- Once technology allowed the cathode ray tubes to be evacuated to a high enough degree, the cathode ray was observed to be deflected by electric fields towards the positive plate. This confirmed that they were negatively charged particles.
- The wave-particle debate was almost settled following the observation of electric field deflection, and the turning of a paddle wheel by the rays.

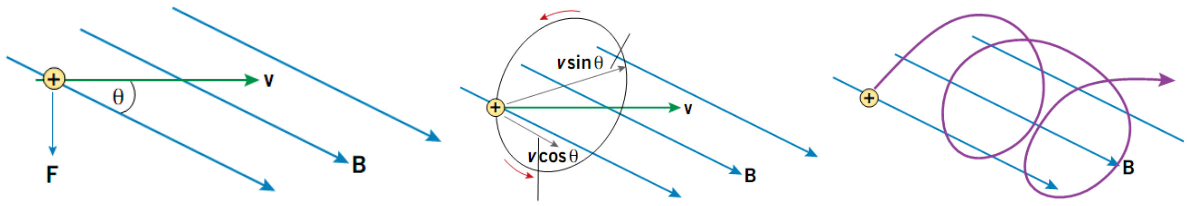
3.1.3 Identify that moving charged particles in a magnetic field experience a force

3.1.4 Describe quantitatively the force acting on a charge moving through a magnetic field

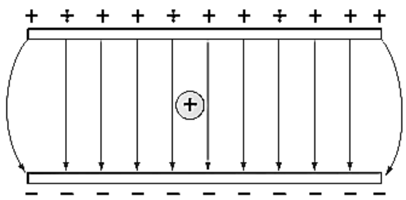
- ***Moving charged particles in a magnetic field experience a force:***

$$F = qvBsin\theta$$

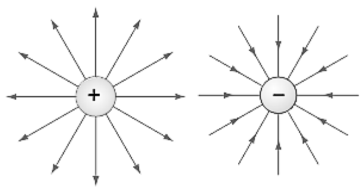
  - q = charge of particle (C); v = velocity (ms^{-1}); B = magnetic field strength (T); θ = angle between direction of charged particle and magnetic field
- The magnetic force acts perpendicularly to the velocity of a particle so it undergoes circular motion.
- A charged particle that enters a B-field with $\theta \neq 0°$ or 90° travels in helical motion (in a spiral); however the component of the velocity at 90° to the field is still circular



3.1.5/3.1.6/3.1.7 Identify that charged plates produce an electric field / Discuss qualitatively the electric field strength due to a point charge, positive and negative charges and oppositely charged parallel plates / Describe quantitatively the electric field due to oppositely charged parallel plates

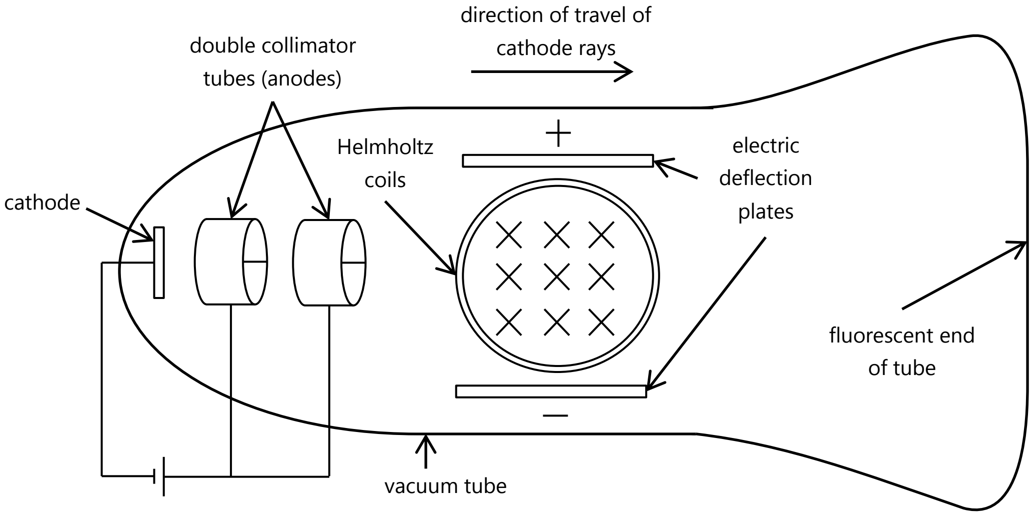


- **Charged plates**
  - Charged plates produce an electric field.
  - The electric field strength due to oppositely charged plates is: $E = \frac{V}{d}$
    - V = voltage (V); d = ⊥ distance between plates (m); E = electric field strength (V/m)
  - Electric fields always go from the positive to negative plate. Diagrammatically, electric fields are represented using field lines: at 90° to surface of plates; evenly spaced; all parallel excluding the final field lines at either end of the plate which are curved outward.
- **Point charges**
  - Symmetrical; radial; at 90° to surface of charge; stronger charges have more dense field lines.
  - Point charges produce radial electric fields which diminish in strength with distance from the point of origin.
  - The direction of the field is pointed radially away from positive charges, and radially towards negative charges.



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

- Thomson's cathode ray tube included a set of charged parallel plates to provide a uniform electric field and wire coils (Helmholtz coils) to provide a uniform magnetic field.
- The fields were at 90° to one another and produced opposing forces on a moving particle.
- Cathode ray particles were produced at the cathode, accelerated and focused by the double collimator anodes, and directed through both the electric and magnetic fields before striking a fluorescent screen on the other end of the cathode ray tube.



- **Equating electric and magnetic field forces**
  - The electric and magnetic field strengths were varied until their opposing forces exactly cancelled, leaving the cathode rays undeflected.
- **Equating magnetic and centripetal forces**
  - The electric plates were then switched off so only the force due to the magnetic field acted on the cathode ray particles. The radius of curvature of the cathode rays was found from the deflection of the beam on the fluorescent screen.
  - The charge/mass ratio of the particles was determined by equating magnetic force with the centripetal force.

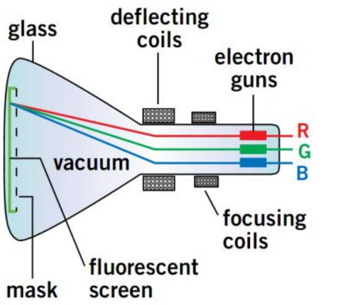
$$\Sigma F = 0$$
$$F_E + F_B = 0$$
In scalar terms, $F_E = F_B$
$$qE = qvB$$
$$v = \frac{E}{B} \ldots(1)$$

$$F_B = F_C$$
$$qvB = \frac{mv^2}{r}$$
$$\frac{q}{m} = \frac{v}{Br}$$
Using (1): $\frac{q}{m} = \frac{E}{B^2 r}$

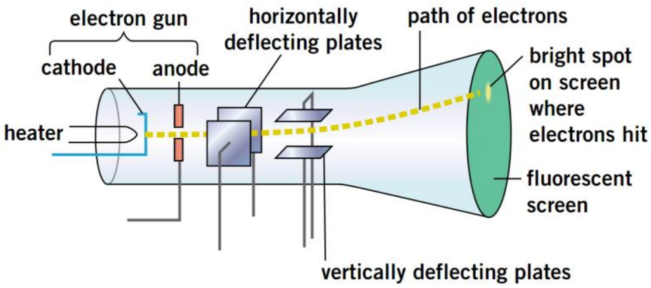
  - E and B can be determined by measuring the size of the applied voltage and current, and the radius r of the arc described by the cathode ray can be measured.
  - Thomson's calculated value for $\frac{q}{m}$ for cathode ray particles was consistently very large (1.76×10^{11} C kg^{-1}), suggesting the existence of a subatomic particle with either a very small mass or a very large charge. Thomson concluded that the size of the particle must be very small, because if the charge was very large, it would not have been contained stably inside an atom.
  - Observations also suggested that this particle was negatively charged; this led to the discovery of the electron. $\frac{q}{m}$ for cathode rays was shown to be the same as for electrons.
  - Thomson's experiment also resolved the wave-particle debate on cathode rays.

3.1.9 Outline the role of electrodes in the electron gun, the deflection plates or coils and the fluorescent screen in the cathode ray tube of conventional TV displays and oscilloscopes

- **Television**:
  - Electron gun
    - This **produces** a narrow beam of electrons using a heating element and thermionic emission.
    - Electrodes at different locations are used to **control the brightness** of the beam, to **accelerate** the beam and then **focus** the electrons along the tube.
    - A television has 3 **electron guns**, each corresponding to one of the primary colours: red, green, blue.
      - » An appropriate electrical signal is given to these guns to build up a colour image.



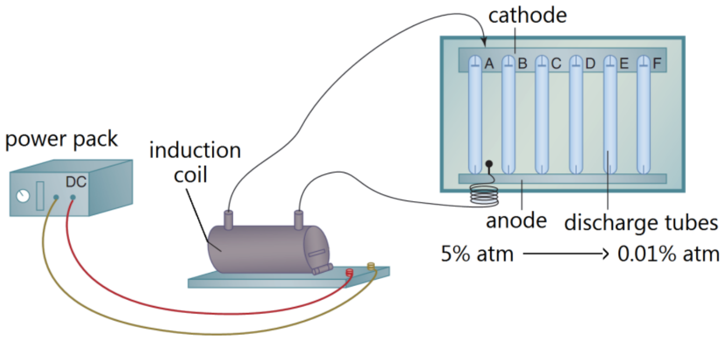
  - Deflection system
    - This consists of **deflection coils**, which allow the cathode rays to be directed across the TV screen at all angles. The current in the coils varies so that the cathode rays are swept across the screen 50 times per second to build up an image. E_K is converted into light.
  - Fluorescent screen
    - This consists of dots of fluorescent paint on the TV screen which, when excited, fluoresce and emit light as a visible output. Once the electron gun produces cathode rays corresponding to the correct colour, they pass through coloured filters then strike the fluorescent dots on the screen to give an image.
- **Cathode ray oscilloscopes (CRO)**:
  - ***A device which is used to view electrical signals in a waveform***
  - Electron gun (*requires a high voltage*)
    - In the CRO, the **electron gun** produces a constant beam of electrons.
    - Electron gun also focuses and directs the electron beam into a narrow, straight path through the deflection system.



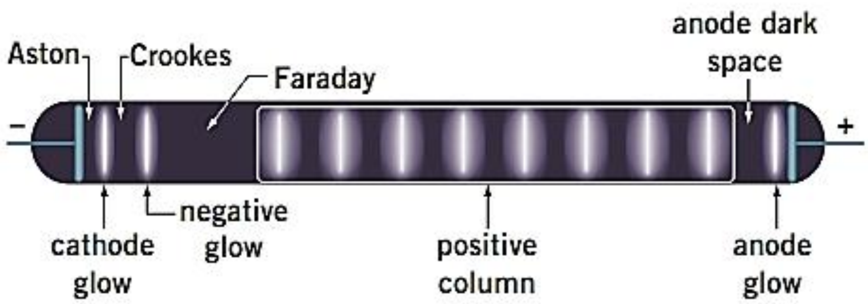
  - Deflection system (*requires a lower voltage*)
    - This consists of 2 pairs of electric deflection plates (one horizontal, one vertical).
      - » **Horizontally deflecting plates** are vertical and are supplied with a time-based voltage, which allows voltage (y axis) to be plotted as a function of time (x axis).
      - » **Vertically deflecting plates** are horizontal and are supplied with the voltage to be measured, and provide the cathode ray with vertical displacement (amplitude) related to its strength and direction.
    - The time-base control allows a variety of sweep rates to be selected (i.e. the "scale" of the horizontal axis changes).
  - Fluorescent screen
    - Provides a trace of the cathode ray movement, giving a visible output representative of the voltage.

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

- Aim: To observe the occurrence of different striation patterns for different pressures in discharge tubes.
- Equipment: discharge tubes, induction coil, power pack, leads, alligator clips.
- Method:
  1. The equipment was set up as shown.
  2. The leads were connected to discharge tube A, and the striation pattern was observed in a darkened room. This was repeated for tubes B → F.

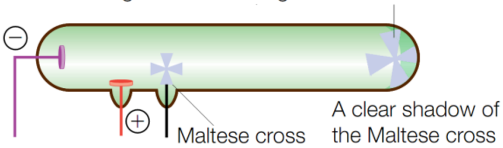


- Results:
  - At 5% atm, long thin purple streamers appeared between the two electrodes.
  - At slightly lower pressures, the streamers change to a soft, pink glow that fills the entire tube.
  - At lower pressures still, the glow broke down into striations (bands of light and dark regions).
  - At even lower pressures, the striation patterns became sharper (more defined), with more dark space between them. A large dark space near the cathode began to form and lengthen towards the anode.
  - At 0.01% atm, the dark space extended throughout the tube.
- Discussion:
  - A discharge tube is an evacuated tube with high voltage across it to give electrons the energy to jump the gap between electrodes. At higher pressures, there is a larger density of gas particles and a higher chance of electrons striking them, so striations are more closely spaced.
  - Different *gases* in discharge tubes produce differently *coloured* discharges.
  - The glowing regions are a result of the electrons (cathode rays) from the cathode carrying different energies. When they collide with the gas molecules in the tube, they cause these gas molecules to become excited and release EMR in the form of different colours.
  - A dark space is the result of electrons having insufficient energy to excite the gas molecules.
  - Some electrons may miss the anode and strike the glass, causing a green fluorescence.
- Risk Assessment:
  - X-rays are produced as a result of cathode rays striking glass or metal within the discharge tube, so stand at least 3 m away from the equipment.
  - The high voltage from the induction coil is a safety hazard. The power should be turned off when not in use. If electricity comes into contact with skin, wash under running water.

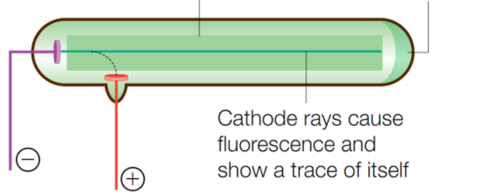


3.1.11 Perform an investigation to demonstrate and identify properties of cathode rays using discharge tubes and analyse the information gathered to determine the sign of the charge on cathode rays

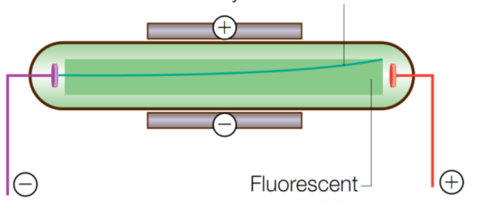
- Aim: To demonstrate and identify properties of cathode rays using discharge tubes.
- Maltese cross:
  - When the cross was down, the entire end of the tube fluoresced green.
  - When the cross was up, a sharp edged shadow in the shape of the cross was cast at the end.
  - *Properties inferred*: Cathode rays travel in straight lines, leave the cathode at 90° and cannot pass through thin metal plates.



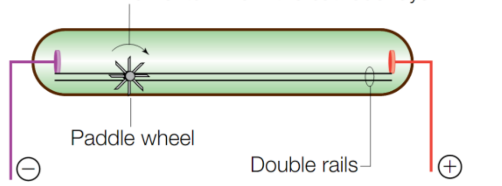
- Fluorescent screen:
  - *Properties inferred:* Cathode rays travel in straight lines (unless deflected) and cause fluorescence.



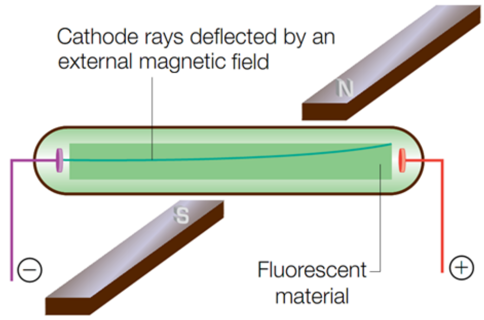
- Electric plates (later experiment):
  - Cathode rays were not deflected by plates initially. This is because early discharge tubes were not sufficiently evacuated, so gas inside the tube became ionised by cathode ray electrons, and these ions would neutralise the electric field.
  - Later, technology was able to create highly evacuated discharge tubes where this did not occur, so cathode rays were deflected towards the positive plate.
  - *Properties inferred*: Cathode rays are negatively charged.



- Glass paddle wheel:
  - When the current was off, the paddle wheel remained at rest.
  - When the current was on, the paddle wheel turned and moved towards the anode.
  - If the cathode and anode were switched, the paddle wheel reversed in direction and again travelled towards the anode.
  - *Properties inferred*: Cathode rays have momentum (and thus, mass) which can be transferred to the paddle wheel.



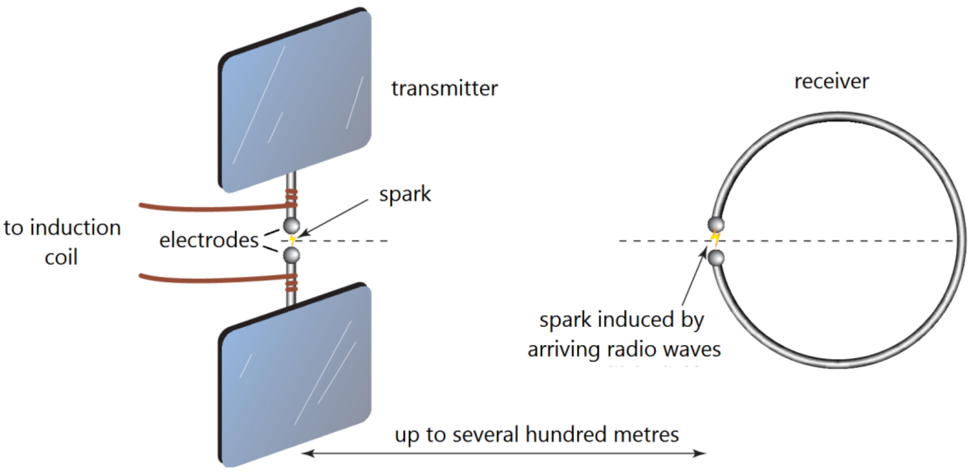
- Magnetic field:
  - The cathode ray was deflected up or down depending on the orientation of the B-field.
  - *Properties inferred*: Cathode rays are negatively charged (since conventional current travels from anode to cathode).



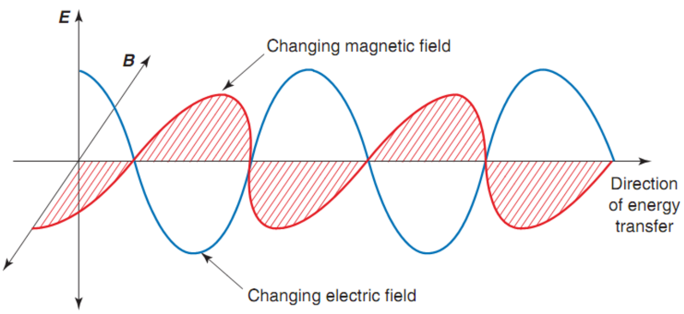
3.2 Photoelectric Effect and Quantised Radiation

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

- <u>Aim</u>:
  - Hertz aimed to produce some of the electromagnetic waves with frequencies and wavelengths other than visible light.
  - In doing so, he was able to confirm Maxwell's predictions that there were electromagnetic waves with frequencies outside the visible light spectrum.
- <u>Set-up</u>:
  - Hertz's apparatus was essentially a radio wave transmitter and receiver.
  - An induction coil was used to create a rapidly oscillating electric field, which caused a rapid sparking across a gap between spherical electrodes in a conducting circuit.
  - This circuit formed the transmitter, and a receiving loop (also with a gap in it) was placed up to several hundred metres from the transmitter.



  - The high voltage flowing through the transmitter from the induction coil produced the rapidly oscillating electric field, which then induced a magnetic field, and so on.



  - Thus electromagnetic radiation (and specifically, radio waves) was produced and traversed the distance to the receiver
  - The electromagnetic radiation struck the electrodes of the receiver, energising electrons in the conducting surface and causing them to jump across the gap as a spark
  - This sparking occurred even though the receiver was not connected to a source of current

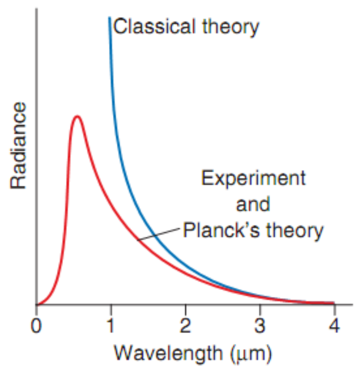
- Observations:
  - When sparking occurred at the transmitter, sparks were also observed to jump across the gap at the receiver.
  - Hertz also performed investigations to determine the properties of waves induced by the transmitter:
    - **Reflection**: Hertz reflected the waves off a zinc plate and they still reached the receiver to cause sparking.
    - **Refraction**: Radio waves were refracted through a prism in the same way as light.
    - **Polarisation**: Hertz rotated the receiver so that its plane ranged from parallel to perpendicular to the transmitter. He observed that the intensity and length of sparking at the receiver was a maximum when the plane of the receiver was parallel to the transmitter, and a minimum (no sparking) when the planes were perpendicular. This showed that, like light, the radio waves produced could be polarised.
    - **Interference**: Hertz observed that waves reaching the receiver from 2 different paths interfered constructively and destructively to produce an interference pattern of light and dark patches.
    - **Sparking across a distance**: Hertz found that the length and intensity of sparking at the receiver was not affected by the distance between the transmitter and receiver. This suggested that radio waves were self-propagating.
    - **Speed**: Hertz was able to accurately measure the speed of the radio waves, and found that it was equal to the speed of light, c.
- Conclusion:
  - These observations provided strong supporting evidence for Maxwell's predictions of electromagnetic radiation and a **model of light**: self-propagating, transverse waves of alternating electric and magnetic fields that are perpendicular to one another.
  - Hertz concluded that radio waves were able to cause sparking at the receiver.
- Photoelectric effect:
  - ***The photoelectric effect is the emission of electrons from the surface of a conductor when it is struck by light***.
  - The effect was first observed by Hertz as he was investigating the production and detection of electromagnetic waves using a transmitter and receiver.
  - The metal of the receiver loop emitted electrons when struck by UV light, which assisted in producing the spark and allowed it to occur across a wider gap.
  - He observed that:
    - The length and intensity of sparking at the receiver was reduced when glass (which blocked UV) was used as a shield between transmitter and receiver.
    - When quartz (which does not block UV) was used, there was no change to the length and intensity of sparking.
    - When a mercury vapour lamp (which emits UV radiation) was shone onto the receiver, the length and intensity of sparking at the receiver was increased.
  - He named these observed effects the photoelectric effect, but did not investigate any further.

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

- In order to prove that radio waves, which allowed sparking to be "transferred" from transmitter to receiver, were electromagnetic waves, Hertz carried out experiments which showed that these invisible waves had similar properties to light.
- He was able to show that the waves:
  - Could interfere
  - Could be reflected and refracted
  - Are polarised
  - Have speed c
- Measuring the speed of radio raves:
  - Hertz measured **frequency** (Hz) and **wavelength** (m) to determine the **velocity** of radio waves: $v = f\lambda$.
  - He used a determined frequency from an oscillating circuit and a measured wavelength determined by interference effects.
  - Hertz determined λ by reflecting the radio waves off a metallic surface and measuring the wavelength of the standing wave set up by interference.
  - Hertz used a different frequency and found that the speed of the waves remained the same - this supported Maxwell's theory that the speed of all electromagnetic radiation was the same.
- Conclusion:
  - Hertz then found that $v = c$ (speed of light) for radio waves ($v = f\lambda$).

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

- ***A black body is one that absorbs or emits all incoming radiation***.
- Planck's hypothesis:
  - ***The radiation emitted and absorbed by the walls of a black body is quantised, occurring in energies*** $\mathrm{E} = \mathrm{hf}$.
- Classical physics previously predicted, using the wave model for the radiation of energy, that as the wavelength of a wave decreased, the radiation intensity of that wave would increase.



- Experimentally, this would mean that as a black body became hotter, a graph of radiation intensity against wavelength would rise infinitely as wavelength approached zero.
- This is in violation of the conservation of energy, since there exists a finite amount of energy in the universe.
- This effect was called the 'ultraviolet catastrophe'.
- Experimental measurements of black body radiation yielded a curve which did not match the theoretical predictions of classical physics.
- This led Planck to his hypothesis: that the radiation emitted and absorbed by a black body occurs in discrete amounts called quanta, rather than as a continuous stream with a wave nature.
  - Each quanta is produced by an atomic oscillation of an atom in the black body.
  - Energy of the quanta is $E = hf$ (where h is Planck's constant).
- Most of the energy is emitted at a peak wavelength dependent on the temperature.

3.2.4 Identify Einstein's contribution to quantum theory and its relation to black body radiation

3.2.5 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

- Important definitions:
  - **Photoelectric effect**: The emission of electrons from the surface of a conductor when light hits it.
  - **Photoelectrons**: Electrons emitted from the surface of a conductor by the photoelectric effect
  - **Stopping voltage**: The minimum voltage required to reverse the charges of the anode and cathode sufficiently in order to stop the flow of photoelectrons (i.e. current drops to 0).
  - **Work function** (*binding energy*): The minimum energy required to cause the emission of an electron from a metal surface (i.e. overcome the attraction between the conductor surface and an electron).
  - **Threshold frequency**: The minimum frequency of light required to just overcome the work function (i.e. cause the photoelectric effect).
- Einstein's contribution to Quantum Theory:
  - Previous to Einstein, Planck had been the first scientist to suggest that energy was quantised, applying this to the energy emitted and absorbed by a black body.
  - Einstein extended this idea about the quantisation of energy in black bodies to all light, suggesting that light occurred in discrete packets, each with energy $E = hf$.
  - With this quantised particle model of light, Einstein was able to solve problems which were observed in the photoelectric effect:
    - Classical physics had previously predicted that the energy of light increased as the intensity of the beam increased. This suggested that the kinetic energy of the photoelectrons would be determined by the intensity of the light beam as well. Therefore the energy required to stop the photoelectrons would also increase with the intensity of light.
      - » **The intensity problem**: However, experiments showed that the kinetic energy of photoelectrons was dependent on the frequency of the light, and the stopping voltage was independent of the light intensity.
    - Classical wave theory also predicted that the energy from light waves would be absorbed by the metal and accumulate until the kinetic energy of the photoelectrons increased to such an extent that they were ejected from the metal's surface. If the intensity of light was high, electrons would be ejected almost immediately. At lower intensities, however, it was thought that some time would pass before photoelectrons were seen.
      - » **The time delay problem**: Experiments found that light of sufficient frequency would cause the emission of electrons *immediately* even if the intensity was not very high.
    - According to classical physics, if the energy of waves was determined by their intensity, then the photoelectric effect should occur for all frequencies of light, provided that the light was of sufficient intensity.

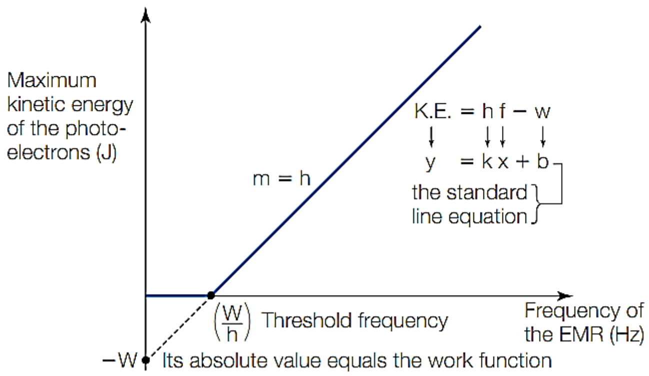
- » **The frequency problem**: However, experiments showed that there existed a threshold frequency below which conductors did not emit photoelectrons at all, irrespective of the intensity of light.

– Einstein was able to explain the photoelectric effect using quantum physics, suggesting that:

- Photons had energy dependent upon frequency: $E = hf$.
  - » **Thus the kinetic energy of photoelectrons and their stopping voltage would depend on the frequency of the incident light waves**.
  - » Light of higher frequency (beyond the threshold frequency) causes the emission of photoelectrons with higher kinetic energy.
- **The rate of emission of photoelectrons and thus the magnitude of photocurrent would depend on the intensity of the light** (which is the rate at which photons fall on the metal surface).
- Photons could transfer all or none (not part) of their energy to electrons. Einstein also reasoned that energy was transferred in a collision between *one* photon and *one* electron and no energy would build up, thus there would be no time delay in observing the photoelectric effect.
- This also meant that in order for electrons to be emitted, the energy of incident photons must be sufficient to overcome the work function (W) of the conductor. Below this energy, photons cannot cause electrons to be emitted. This explained the threshold frequency (f_0). Excess energy gives photoelectrons kinetic energy:

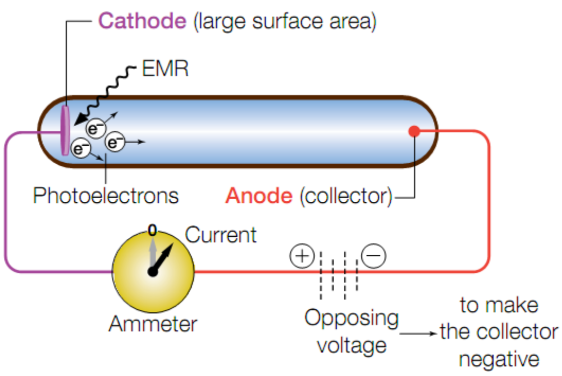
$$E = hf = W + E_{k\,max}$$

$$E_{k\,max} = qV_0 \text{ and } W = hf_0$$



The constancy of h (same gradient of line) means that $E_{k\,max}$ is proportional to the frequency of light

- This set-up can be used to determine the kinetic energy of electrons produced by the photoelectric effect:
  – The aim is to make the collector (anode) negative enough to repel the photoelectrons to prevent them from reaching the collector.
  – Light is introduced onto the metal plate, which emits electrons by the photoelectric effect.
  – The voltage, set initially at $0V$, is gradually increased until the current at the galvanometer reads 0 - this voltage is the



stopping voltage. The voltage applied imparts the work required to nullify the charge of the electrons.
  - The maximum kinetic energy of the electrons ($E_{k\ max}$) can be determined by: $E_{k\ max} = eV_0$.
- The ability of Einstein's prediction of quantised light particles - to explain what classical physics could not - lent significant support to quantum theory.
- The particle properties of light described by Einstein were also the first step towards de Broglie's hypothesis of the wave-particle duality of matter - a cornerstone of modern quantum physics.
- Therefore Einstein's predictions were an initial step towards the development of quantum theory as we know it.

3.2.6 Explain the particle model of light in terms of photons with particular energy and frequency

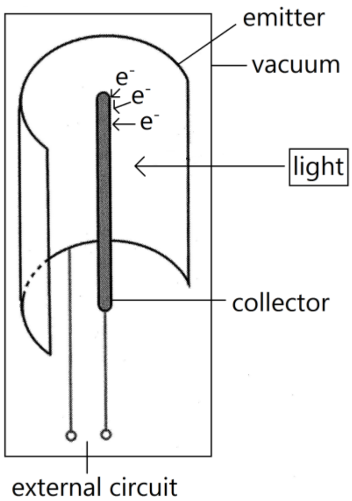
3.2.7 Identify the relationships between photon energy, frequency, speed of light and wavelength

- Light is considered to consist of a stream of particles, or discrete bundles of energy, called photons.
- Photons carry an amount of energy that is proportional to the frequency of radiation:

$$\left.\begin{aligned} E &= hf \\ c &= f\lambda \end{aligned}\right\} E = \frac{hc}{\lambda}$$

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

- ***A photocell is a device which uses a light source to produce a photocurrent***.
- This light source is directed towards a metal plate and excites electrons in the metallic surface, causing them to be emitted by the photoelectric effect
- The metallic surface is curved so that photoelectrons are focused towards the collecting electrode, and pass through an external circuit as a current.
- Uses:
  - Often, photocells are used in motion detectors, light detectors and security cameras.
  - If the light beam is interrupted, the lack of photocurrent triggers an alarm.



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

- Planck was a nationalist and used his scientific research to support political Nazi movements.
- Einstein, however, was a pacifist and preferred world peace. He maintained that scientific research should be removed from social and political forces, and devoted to the pursuit of knowledge.

- On September 1914, Planck signed the 'Manifesto of the 93 German intellectuals to the civilised world' in support of the growing militancy of the German regime.
- Einstein with three others signed a counter manifesto in opposition.
- Planck supported the Nazi regime and was appointed president of the Kaiser-Wilhelm Institute for scientific research which contributed to the war effort.
- Einstein fled Germany, refusing to support the Nazi movement.
- Einstein wrote to President Roosevelt and encouraged the development of the Manhattan Project, an American nuclear research effort aimed at preventing the scientific development of a German nuclear bomb which would be misused in order to advance the Nazi's political and social goals.
- Einstein is noted for his total opposition to all war, and later regretted urging the development of the atomic bomb.

3.2.10 Perform an investigation to demonstrate the production and reception of radio waves

- Aim: To demonstrate the production and reception of radio waves.
- Equipment: induction coils, radio, power pack.
- Method:
  1. The induction coil (attached to the power pack) and radio receiver were placed at opposite ends of a room facing one another.
  2. The radio was tuned to a static channel and the induction coil was switched on.
  3. Changes in the loudness of the static coming from the radio were observed.
  4. The radio was moved along the length of the bench with the induction coil still on, and once again changes in loudness were noted.
- Results:
  - When the radio was producing static and the induction coil was on, sparking at the coil correlated to an increase in the volume of static at the radio.
  - As the radio was moved along the bench, the static volume changed so there was an alternating pattern of increasing volume, reaching its loudest, followed by a decrease in volume to reach its softest, and so on.
- Discussion:
  - The induction coil acts as a source of radio waves, which are received by the radio and cause static to be heard.
  - As the radio is moved along the bench, the relative maximum and minimum static volumes correlate with relative maxima and minima (constructive/destructive interference) in an interference pattern.
- Risk Assessment:
  - High voltage from the induction coil presents a risk of electrocution.
  - X-rays are produced, so stand at least 3 m away from the equipment.

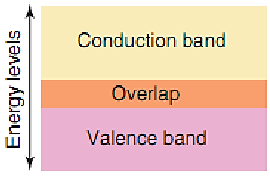
3.3 Semiconductors and Transistors

3.3.1 Identify that some electrons in solids are shared between atoms and move freely

- ***Some electrons in solids are shared between atoms and move freely***.
- In metals, a lattice of positive ions is surrounded by a 'sea' of delocalised valence electrons which are free to move between atoms. These electrons are able to conduct electricity.
- In insulators, atoms are held in a lattice structure by strong covalently bonded electron pairs. These electrons are not free to move and so cannot conduct electricity.

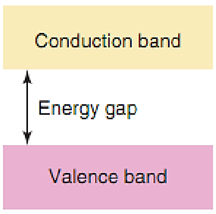
3.3.2 Describe the difference between conductors, insulators and semiconductors in terms of band structures and relative electrical resistance

- In atoms, electrons exist in discrete energy levels or "shells", in which they have a certain, well-defined amount of energy. The highest energy level occupied by electrons is the valence shell.
- If many of the same atoms are brought close together (as in a solid), the electron shells of the atoms exist in a continuous energy "band". These energy bands are separated by intermediate zones called *forbidden energy gaps* (or *zones*), which cannot be occupied by electrons.
- In solids, the highest/outermost energy band in which electrons exist in an unexcited state is the valence band. Above this is the conduction band, in which excited electrons may move freely and conduct electricity. Between these two bands there exists a forbidden energy gap which electrons must cross to move from valence to conduction band.
- **Conductors**:



(a) Conductor

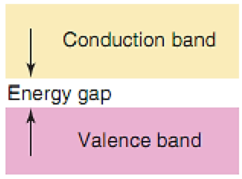
  – Properties:
    ▪ Electrically conductive
    ▪ Very low electrical resistance
    ▪ As temperature increases, resistance increases and conductivity decreases
  – In conductors, the valence and conduction bands are touching or overlap, so that there is no forbidden energy zone between these bands. This allows electrons to move into the conduction band with very little additional energy/excitement, where they may conduct electricity with low resistance. Electrons in conductors therefore do not remain attached to individual atoms, but surround the ion-lattice structure as a sea of delocalised electrons, which may drift and facilitate current flow when an electrical potential is applied.
  – If the temperature of a conductor is increased, the vibration of ions about their equilibrium lattice positions increases. Therefore the number of collisions occurring between ions in the lattice and electrons increases, hindering the straight movement of electrons in the conduction band and increasing the resistivity of the conductor.
- **Insulators**:



(c) Insulator

  – Properties:
    ▪ Not electrically conductive
    ▪ High electrical resistance
  – Often insulators are covalently bonded structures (i.e. electrons exist in shared pairs and completely fill the outer valence shell).

  - There is a large forbidden energy gap between full valence bands and empty conduction bands. It is very difficult for electrons to obtain sufficient energy to jump over this forbidden energy zone and enter the conduction band. Thus there are no free charge carriers to facilitate current flow, so insulators have high resistance.
- **Semiconductors**:
  - Properties:
    - More electrically conductive than insulators
    - Less electrically conductive than conductors
    - As temperature increases, conductivity increases and resistance decreases



(b) Semiconductor

  - Semiconductors are usually covalently bonded group IV atoms.
  - They have smaller forbidden energy zones than insulators, but larger than conductors.
  - At low temperatures, the valence band is completely occupied and the conduction band is empty, so conductivity is low and resistance is high.
    - At absolute zero ($T = 0\ K$) there is no thermal energy available for electrons, so the semiconductor behaves as an insulator.
  - At higher temperatures, thermal oscillations of the crystal lattice structure provide electrons with sufficient energy to jump across the forbidden energy gap, thus increasing the number of free charge carriers in the conduction band which facilitate current flow and reduce electrical resistance.
  - The net absence of an electron in the valence band also creates a positive hole which is able to carry positive current in the opposite direction to electrons.

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

- In semiconductors with sufficient thermal energy, some electrons in the valence band are able to cross the forbidden energy gap and enter the conduction band.
- ***The net absence of an electron in an otherwise full valence band is known as a positive hole***.
  - ***Holes are able to act as positive charge carriers and move in the direction of conventional current***.
- Positive current flow relies on the movement of holes from single atom to the adjacent atom.
  - Thus, conduction is possible in both the conduction band as a flow of electrons and in the valence band as a flow of positive holes.
- The speed of electron current is much faster as electrons are able to freely flow through the conduction band, whereas current flow due to "holes" in the valence band is considerably slower.
- Electrons and positive holes move in opposite directions.

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

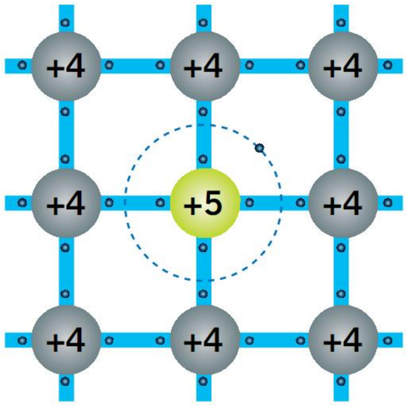
- Conductors have many electrons in the conduction band which are able to act as free charge carriers and move between atoms.
- Semiconductors have few free electrons in the conduction band (though this increases if heat or light energy is applied).
- Insulators have no free electrons in the conduction band.

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

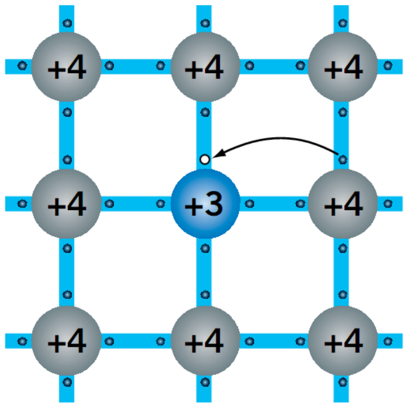
- ***A transistor is a semiconducting device used to amplify and/or switch electric current***.
- **Germanium** was the first element to be used in early transistors as it was the only element which could be purified to a sufficiently high level required for semiconductor devices.
  - Disadvantages with the use of germanium:
    - When germanium gets hot, it becomes a relatively good conductor, allowing too much current to pass through components, which can damage electrical equipment.
    - Germanium is a rare element, so it is costly.
- **Silicon** eventually replaced germanium as the semiconducting material of choice in transistors, as it overcame the problems with germanium:
  - Silicon can be extracted from silicon dioxide (sand), which is abundant and cheap.
  - It retains its semiconducting properties at relatively high temperatures.
  - It forms thin oxide layers which can be doped with impurities for use in transistor technology.
  - Processing techniques were developed to produce very pure, single crystal forms of silicon, which have a uniform molecular structure and thus consistent properties.

3.3.6 Describe how 'doping' a semiconductor can change its electrical properties

- ***Doping is the addition of a tiny amount of an impurity (a dopant) into an otherwise pure crystal lattice in order to enhance the electrical properties of a semiconductor***.
- Addition of Group V dopant (n-type):
  - Atoms of group V elements have one more electron in their valence shell than group IV atoms.
  - When a group V impurity is substituted into an otherwise pure semiconducting lattice structure, 4 of its 5 valence electrons form bonds with adjacent atoms, but one remains unbonded. This additional electron can be easily promoted to the conduction band where it acts as a free charge carrier, increasing the free negative charge carrier density. This therefore increase electrical conductivity and reduces resistance.

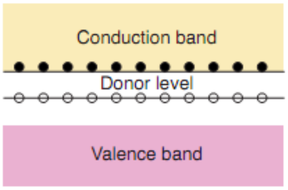


  - The majority of charge carriers in semiconductors doped with group V elements are negative, thus these semiconductors are "n-type".
- Addition of Group III dopant (p-type):
  - Atoms of group III elements have one less electron in their valence shell than group IV atoms.
  - When a group III impurity is substituted into an otherwise pure semiconducting lattice, its 3 valence electrons form bonds with surrounding atoms. The absence of a 4th electron incorporates a positive hole into the lattice which is able to act as a positive charge carrier in the valence band. This therefore increases the free positive charge carrier density, increasing its electrical conductivity.

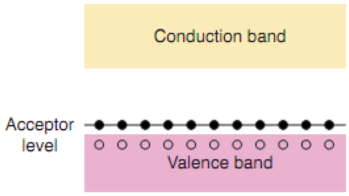


  - The majority of charge carriers are positive, thus this is a "p-type" semiconductor.

- Both n-type and p-type semiconductors remain electrically *neutral* when doped, despite the creation of an unbonded electron or hole (neutral impurity atoms were added to an already neutral solid, so net charge is 0).



n-type semiconductor



p-type semiconductor

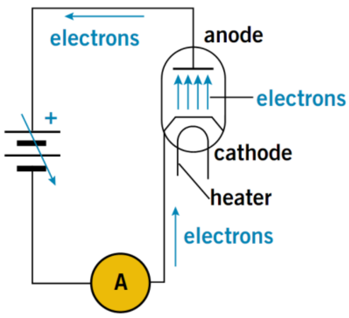
- Since electrons have much greater mobility than positive holes, n-type semiconductors conduct better than p-type semiconductors.

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

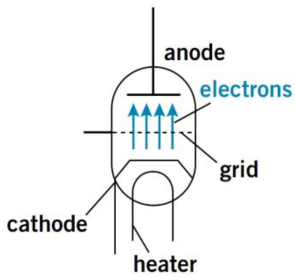
- Semiconductors can be classified as *intrinsic* semiconductors (semiconducting properties occur naturally) or *extrinsic* semiconductors (which have other types of impurities added).
- <u>n-type semiconductors</u> (formed by doping with *group V* elements):
  – The majority of charge carriers are electrons due to the addition of the dopant (i.e. extrinsic semiconductor properties). However a minority of charge carriers are positive holes due to the natural excitement of an electron into the conduction band creating a hole (i.e. intrinsic semiconductor properties).
- <u>p-type semiconductors</u> (formed by doping with *group III* elements):
  – Majority of charge carriers are positive holes due to doping with group III element (extrinsic properties). The minority of charge carriers are negative electrons (intrinsic properties).

3.3.8 Describe differences between solid state and thermionic devices and discuss why solid state devices replaced thermionic devices

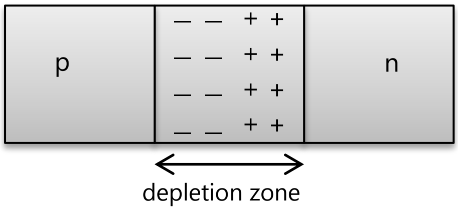
- ***Thermionic devices are those which use the thermionic emission of electrons within a vacuum environment in order to rectify or amplify current***.



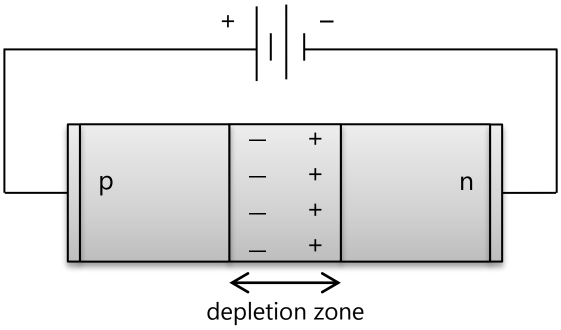
- A negative filament is heated sufficiently to allow thermionic emission of electrons from its surface. These electrons move towards a positively charged electrode at the other end of the vacuum flask.
- A **diode** is an electronic device which only allows electric current to flow in one direction, so it can be used as an electronic switch and for converting AC to DC current (rectification).
  – Thermionic emission is the process by which current is *rectified*:
    ▪ If the heater (filament) is negative and the anode is positive, electrons will flow.
    ▪ If the supply current is reversed, then electrons will not travel towards the electrode and no current will flow.
  – The supply current is the current to be rectified.
- In **triodes**, electrons are accelerated through a metallic grid, which allows the *amplification* of current.
  – Electron current can be stopped by placing a negative voltage on the grid, or allowed through by using a positive voltage. A voltage between these two extremes can be used to control the amount of current flowing through.



- ***Solid state devices are those which use semiconductors and the properties of p-n, p-n-p or n-p-n junctions to direct the flow of electrons***.
- The junction (or interface) between a p-type semiconductor and an n-type semiconductor acts as a diode, allowing current to flow in one direction only.
- <u>Operation of a p-n junction</u>:
  - Electrons close to the p-n junction tend to diffuse from the n-type across the interface, and combine with positive holes in the p-type semiconductor.
  - This movement of charge creates a net potential difference across the junction, setting up an electric field that goes from n→p type semiconductor.

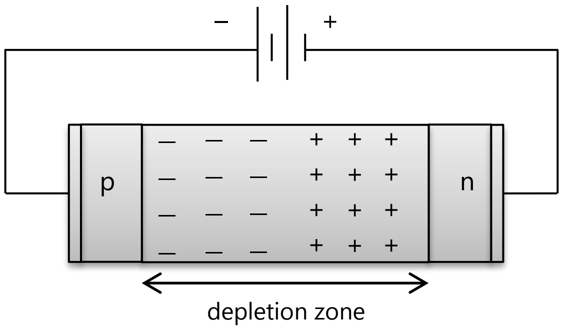


  - This electric field acts as a potential barrier against the further diffusion of charge across the junction, and is called the '**depletion zone**'.
  - If a voltage is applied to a p-n junction, it will act as a diode, allowing current to flow from p-type to n-type.
  - The application of current can be either 'forward' or 'backward/reverse' biased:
    - **Forward biased**
      - A forward biased diode has positive current applied to the p-type and negative current applied to the n-type.
      - The flow of negative current (electrons) into the n-type repels the electrons already present in the doped semiconductor, forcing them to move towards the depletion zone where they effectively neutralise the positive charge at the junction.



      - Similarly, positive holes in the p-type will move towards the depletion zone and neutralise negative charges at the junction.
      - Effectively, this creates an electric field opposing that in the depletion zone. This lowers the junction field strength and decreases the potential difference across the p-n junction (i.e. 'narrows' the depletion zone).
      - Eventually, the movement of charge across the junction will no longer be opposed by the potential barrier across the depletion zone, thus allowing the flow of conventional current from p-type to n-type.
      - A current that passes through a forward-biased diode will lead to some recombination of electron and hole pairs. This occurs when a conduction electron drops to the valence band to occupy a hole This change in energy appears as heat or light, with the energy of the photon equal to the energy lost by the electron: $E = hf$.

- **Backward/reverse biased**
  - » If voltage is applied so that the positive terminal is directed towards the n-type and the negative terminal to the p-type, the influx of positive charge to the n-type will attract electrons in the semiconductor away from the p-n junction.



  - » Effectively, the electric field strength in the junction is increased.
  - » This increases the potential difference across the junction (i.e. 'widens' the depletion zone).
  - » It is very difficult for charge carriers to obtain sufficient energy to overcome the strong electric field and cross the depletion zone, so no current will flow through the conductor (the diode in this case acts as a large resistor).

- ***A transistor is a semiconductor device that controls or amplifies electrical current***.
  - – Transistors have largely replaced thermionic devices.
  - – Transistors use p-n-p or n-p-n junctions. A small *drain current* is supplied to the thin middle layer to allow a large current flow through the device, amplifying current.
- <u>Reasons why solid state replaced thermionic</u>:

Thermionic	*Solid state*
» **Large energy requirements** – requires thermionic emission of electrons using a separate voltage	» **Lower energy requirements** – use the properties of a p-n junction, and do not require separate voltages
» Requires **vacuum conditions** to allow functioning	» **No particular air pressure** condition required for operation
» **Unreliable** – glass tubes and solder joints are fragile, allowing air into the tube which stops the device from working	» **More reliable/robust** – no need for complicated wiring or glass tubes, so they are less prone to failure/malfunction
» Often **bulky** due to vacuum tubes and protective packaging, reducing the portability of devices and limiting their widespread use	» Allow **miniaturisation** and increased **portability** of devices – p-n junctions are much smaller than vacuum tubes in thermionic devices, and do not require protective packaging
» **Energy inefficient** – produces lots of **heat**, which may damage surrounding electrical components, making thermionic devices unsuitable for use in computer technologies	» Greater **energy efficiency** – produces much less heat, so does not pose a risk to surrounding components; thus suitable for use in computer technologies
» **Time delay** before the device works – takes time to heat up and allow current to flow; electrical signal transfer is also slow	» Allows **immediate current flow**, and electrical signal switching occurs rapidly
» Often very '**noisy**' and **insensitive** – cannot be used to amplify weak or high frequency radio signals, limiting their use in long distance radio communications	» Very '**quite**' and **sensitive** – able to detect and amplify weak or high frequency radio signals for long distance communications
» Overall, devices have a large energy requirement, complicated wiring, low radio sensitivity, and the maintenance required due to the unreliability of devices increases the cost of production, use and maintenance	» Overall, increased reliability, energy efficiency, portability, speed of operation, and the ease of construction and maintenance makes solid state devices much cheaper, more robust and desirable to use

- Both types of devices can:
  - Rectify – convert AC to DC, allowing current to flow in one direction only.
  - Amplify – convert low voltage/current signal to a higher voltage/current.
  - Switch – control whether a voltage is applied to a particular part of a circuit.

3.3.9 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

- During WWII, the increased need for more efficient and sensitive radar and radio communications sparked research into transistors.
- The vacuum tube thermionic devices used at that time were fragile, bulky, energy consuming and inefficient, noisy, insensitive and unreliable.
- Scientists began researching other materials and their applications to replace thermionic valves in their respective applications.
  - They were looking for a transistor which was compact, power efficient, mechanically rugged and able to operate high switching speeds to replace the thermionic valve.
- This led to research into materials that could be used in transistors, particularly semiconductors such as silicon and germanium, increasing the knowledge of properties of these semiconductors.
- Initially, germanium was used instead of silicon because of the inability of current technologies to purify silicon to required concentrations.
- However, germanium lost its semiconducting properties at high temperatures (became too conductive) and is rare and expensive, so it became necessary to develop more reliable semiconductors.
- With further research and advances in technologies (e.g. silicon purification), silicon came into use.
  - Silicon could also be made into thin oxide layers, allowing the miniaturisation of transistors and increasing the overall portability of communication technology.
- With further understanding of semiconductors, doping was invented, increasing the versatility of transistors and the scope of applications for which they can be used.

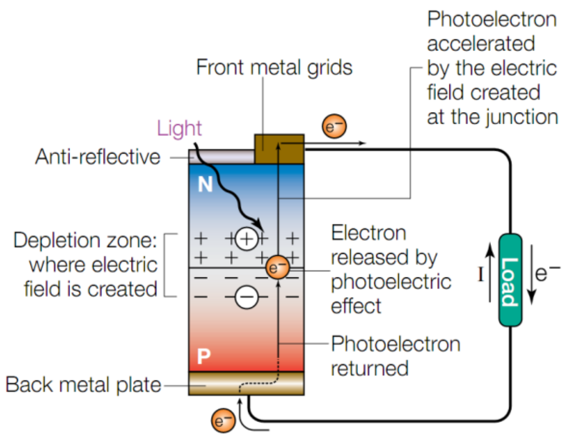
3.3.10 Identify data sources, gather, process, analyse information and use available evidence to assess the impact of the invention of transistors on society with particular reference to their use in microchips and microprocessors

- The invention of transistors led to the development of integrated circuits in microchips and microprocessors which are used in computers and computer-based technologies.
- A **microchip** is an assembly of electronic devices in a single chip, which is designed to carry out specific tasks as they would if they were made individually and connected by wires.
  - Microchips are also called integrated circuits.
- A **microprocessor** is a type of microchip that contains complex electronic devices to perform arithmetic, logic and control operations. It is a more complicated form of a microchip.
  - The rise of microprocessors is due to the ability to integrate many electronic devices into a single chip; the more devices integrated into a single chip, the more powerful the chip.

- <u>Advantages</u>:
  - The ability to *integrate* many electronic devices into a single chip has increased its power:
    - As the number of semiconductor devices on a single chip increases, the devices are placed closer to each other, so signal transmission between devices becomes more efficient due to smaller operating distance.
    - The power dissipation during operation is also reduced due to the small distance of separation, resulting in less resistance to electric signals and thus less heat loss.
  - Transistor technologies have been integrated into many forms of electronic devices, such as medical appliances (pace-makers, hearing aids, breathing assistance), biotechnology and telecommunications, improving quality of life.
  - The further development of microprocessors enabled computer-based technologies to be developed. Automated technology has contributed to the efficiency of industry, improving the precision, predictability and speed of production and reducing the cost to consumers.
  - Computer-based technologies have:
    - Increased our ability to store and transfer information via the World Wide Web.
    - Increased the ease and convenience of communication (e.g. via mobiles phones, email).
    - Created jobs, such as in information technology and software design and development.
    - Allowed new safety features in cars, trains and planes to be created.
    - Created new leisure activities such as video games.
- <u>Disadvantages</u>:
  - Automation of industry has reduced the need for unskilled labour, causing loss of jobs.
  - Increased reliance on computer technology.
  - Privacy and copyright issues.
- <u>Overall</u>: The advantages of transistor technology used in computer microchips and microprocessors far outweigh their disadvantages. Thus they have a positive impact on society.

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

- ***A solar cell converts sunlight energy into electrical energy; it uses a p-n semiconducting junction***.
- For a solar cell to work, the n-type semiconductor is exposed to sunlight, while the p-type is not.
- At the p-n junction, electrons flow from n to p-type, setting up an electrical potential gradient across the depletion zone, which eventually prevents the further flow of electrons.
- When a photon strikes an electron in the depletion zone, it is liberated (by the photoelectric effect) and accelerated towards the n-type layer by the electric field; this creates a voltage difference between the n and p-type layer.

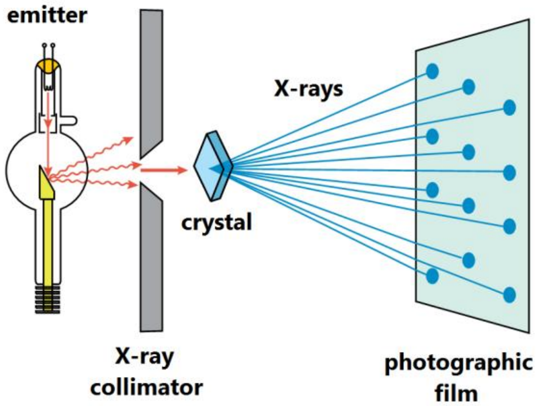


- As a result, the excess electrons in the n-type flow into electrical contacts created by a fine metal grid and through an external circuit to do work before reaching the p-type layer to replenish the overall electron deficiency.

3.4 Superconductors

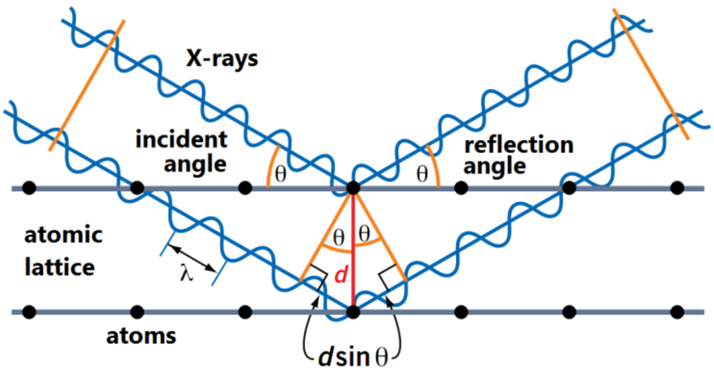
3.4.1 Outline the methods used by the Braggs to determine crystal structure

- Sir William Henry Bragg and his son, Sir William Lawrence Brag, developed an **X-ray spectrometer** to systematically study the diffraction of X-rays from crystal surfaces in order to determine crystal lattice structure.
- They proposed that **X-rays**, because of their **short wavelengths** (in the order of magnitude of interatomic spaces), could be diffracted off the atomic planes within a crystal lattice surface.
- A monochromatic X-ray beam (of known wavelength) from an X-ray tube was directed at the surface of a crystal lattice, which was placed at an angle θ to the X-ray beam.
- The X-rays were absorbed and re-emitted by the different planes of the lattice, and were measured by a detector or photographic film.
- The diffraction of X-rays by the crystal lattice structure led to their constructive and destructive interference, resulting in an interference pattern of light and dark patches (which could be visualised by the film).



- Based upon the shifting interference pattern of the X-rays, Braggs was able to determine that a crystal has a 3D lattice-like arrangement of atoms.
- A relationship could also be found between the wavelength of X-rays, θ and the interplanar space, d (distance between atoms in the lattice):
  - If X-rays interfere constructively,

$$\lambda = dsin\theta$$
$$\boldsymbol{n\lambda = 2dsin\theta}$$



3.4.2 Identify that metals possess a crystal lattice structure

3.4.3 Describe conduction in metals as a free movement of electrons unimpeded by the lattice

- ***Metals possess a crystal lattice structure***.
- Metals have a crystal lattice arrangement of positive metallic ions surrounded by a 'sea' of delocalised electrons.
- These delocalised valence electrons are shared by all positive ions of the lattice and so are free to move throughout the lattice.
- Conduction within metals can occur through the movement of these delocalised electrons, unimpeded by attachment to individual atoms of the lattice structure.

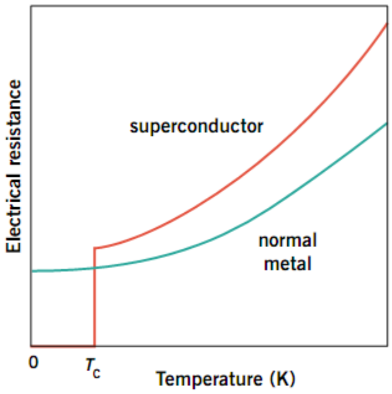
3.4.4 Identify that resistance in metals is increased by the presence of impurities and scattering of electrons by lattice vibrations

- **Chemical impurities** disrupt the structure of the metal lattice and increase the likelihood of electrons colliding with the lattice. This impedes the free movement of electrons through the lattice, thus increasing resistance.
- Free electron movement is impeded by **lattice vibrations**, which increase with increasing temperatures (due to increased kinetic energy). A vibrating lattice collides with free moving electrons, thus deflecting them from their linear movement and causing resistance.
- Note: *Conduction in conductors*
  - When a potential difference is applied to a conductor, electrons will have an overall 'drift' velocity towards the positive terminal.
  - If no voltage is applied, electrons are moving equally in all directions, so the net drift is zero.

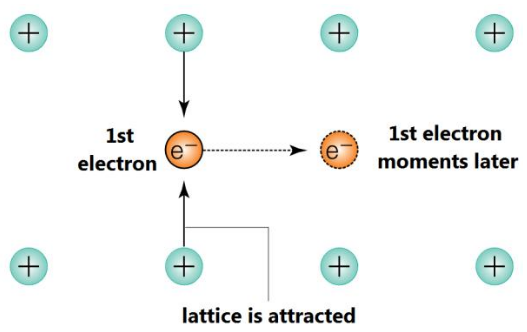
3.4.5 Describe the occurrence in superconductors below their critical temperature of a population of electron pairs unaffected by electrical resistance

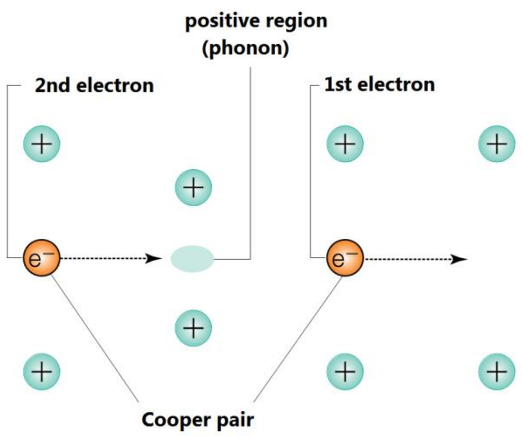
3.4.6 Discuss the BCS theory

- ***Superconductivity is the phenomenon exhibited by certain metals (type 1 superconductors only) where they will have no resistance to the flow of electricity when their temperature is cooled below the critical temperature***.
- In superconductors above the **critical temperature** (T_c) of normal conductors, the thermal vibrations of the lattice structure lead to collisions between electrons and the lattice, which impede electron movement and contribute to the resistance of these materials.



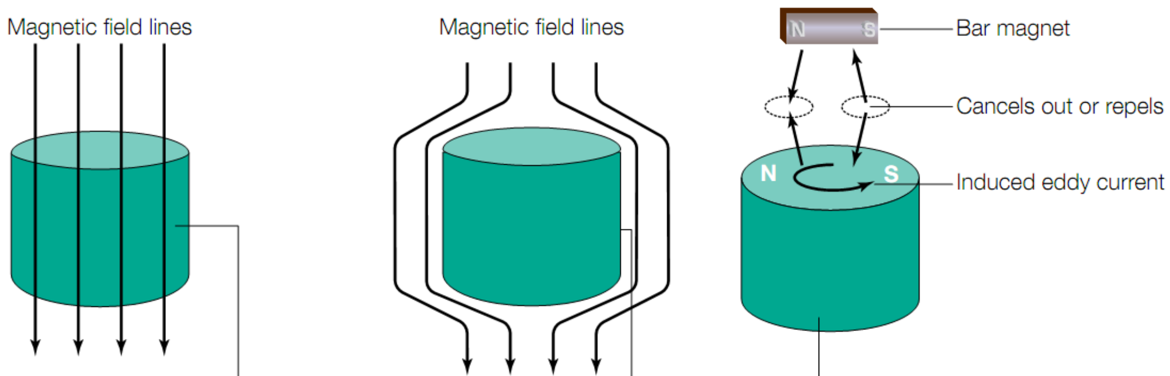
- BCS theory (Bardeen, Cooper and Schrieffer) describes the occurrence of electron pairs and phonons in superconductors below their critical temperature, allowing the movement of electrons without collisions or resistance.
- Below the critical temperature, lattice vibrations in a superconductor become negligible, so the predominant interaction between electrons and the lattice structure is *electrostatic attraction*.
- An electron moving through the lattice will attract positive ions towards itself to create a '**trough**' of concentrated positive charge density, which attracts a 2nd trailing electron, creating a **Cooper pair** with the 1st electron.
- The distortion of the crystal lattice by the leading electron creates/emits a packet of vibrational energy (a **phonon**) which is absorbed by the trailing electron (phonons hold electrons together).
- This transfer of energy allows the electrostatic repulsion existing between negative electrons to be overcome in the formation of Cooper pairs.
- Cooper pairs are continually formed, broken and reformed between different electrons, allowing them to move through the lattice coherently, without collision and thus, **without resistance**.





3.4.7 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

- When a superconductor is exposed to a magnetic field, currents are induced in the surface so as to produce a magnetic field which opposes the direction of the external field (*Lenz's Law*).
- If the superconductor is below the critical temperature, there is no resistance; hence the induced current gives rise to a magnetic field which is equal and opposite to that of the external field.
  - Thus there is no net magnetic field threading the superconductor.
- This is known as the **Meissner effect** – the total exclusion of an external magnetic field from within the superconductor.
- **Magnetic levitation** occurs if the external magnetic field is brought near to a superconductor below its critical temperature.
  - The induced currents in the superconductor create magnetic poles which cause repulsion between the magnet and the superconductor.
  - This repulsive force, due to the 'internal'/induced and external magnetic fields, is sufficient to balance out the gravitational weight force of the magnet, causing it to levitate.
- Hence superconductors below their critical temperature have two important properties:
  - They have *zero electrical resistance* (and so can carry large currents with no heat loss).
  - They demonstrate the *Meissner effect*.



(a) Non-superconductor or a superconductor above its critical temperature
(b) A superconductor below critical temperature
(c) Superconductor below the critical temperature

3.4.8 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

Class of superconductor	Example	Critical temperature (K)
Metals (Type 1)	Mercury	4.12
Metal alloys	Tin-niobium	18
Ceramics	YBCO	90

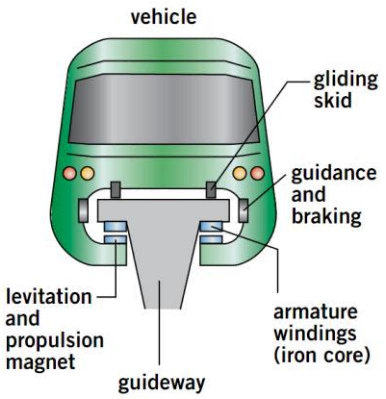
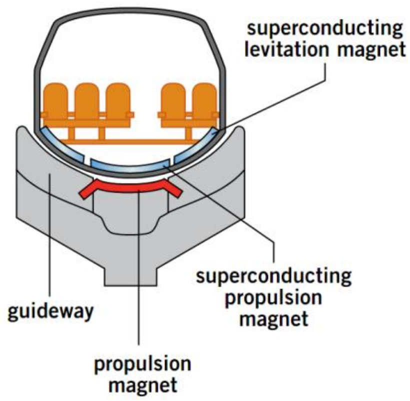
- There are 3 types of superconductors:
  - **Type I** are made of metals, which are more malleable, ductile, tough and easily produced; however they have very low critical temperatures which are technically very hard to reach and maintain.
  - **Type II** are made from alloys, which have higher critical temperatures that can be more easily reached; however they are more brittle and fragile, less malleable, chemically less stable and more difficult to produce.
  - **Ceramics** are superconductors with high critical temperatures.

3.4.9 Discuss the advantages of using superconductors and identify limitations to their use

- Advantages:
  - Superconductors are able to carry large currents with no resistance, and thus no heat.
  - They may be used to produce very strong magnetic fields.
  - These properties are particularly useful in:
    - **Power transmission**: No resistance removes the need for transformers and allows longer distance, cheaper transmission to even the most remote locations.
    - **Magnetic levitation**: This can greatly increase travel speed by removing contact and friction between moving parts.
    - **Generators**: Far more efficient and smaller (no iron core).
    - **Medical imaging**: May be able to detect extremely weak electrical signals in the brain, allowing disorders to be imaged.
    - **Computer chips**: Allow miniaturisation and increased speed.
    - **Current storage**: Using superconducting loops into which current is fed. Generators store electricity generated during off-peak times for use during peak demand periods.
- Limitations:
  - Technical difficulties and expensive costs associated with achieving and reliably sustaining the extremely **low temperatures** required to achieve superconductivity.
  - Higher temperature ceramic superconductors are very **expensive**, limiting their use in everyday applications.
  - Superconducting materials often become very **brittle** at subcritical temperatures, limiting their widespread use in wiring and electrical transmission lines.

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

- Magnetic levitation suspends an object so that it is free of contact with any other surface. This allows frictionless movement of the levitating object, making it useful for high-speed trains.
- A typical maglev train is streamlined to reduce air resistance and travels along a guideway.
  - The main obstacle to higher speeds is air resistance encountered during motion.
- *Propulsion*: Once the train is levitated, a series of attractions and repulsions is generated (by continually changing the polarity of alternate magnets) to provide a net force to accelerate the train along the guideway.
- *Lateral guidance*: Electromagnetic induction in the side of the guideway and the train prevents lateral displacement of the train.
- The superconducting electromagnets rely on the conventional 'like-pole' repulsion (not the Meissner effect) to achieve levitation.
- There are two different types of magnetic levitation systems:

<u>Electromagnetic suspension system</u> **(EMS)** *Used in Germany*	<u>Electrodynamic suspension system</u> **(EDS)** *Used in Japan*
• Based on **magnetic attraction**. • EMS uses conventional electromagnets, mounted under the train, on structures that wrap around the guideway to provide the lift and create a frictionless running surface.  	• Based on **magnetic repulsion**. • EDS uses superconducting magnets on the train (kept cool with liquid helium) and electrically conductive coils in the guideway to levitate the train. 

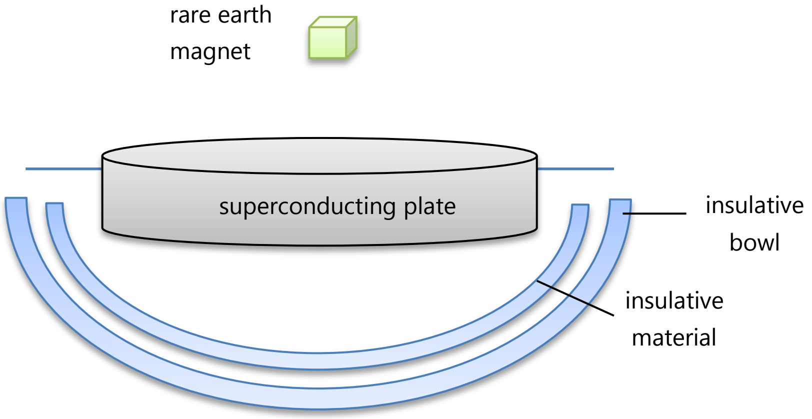
- <u>Advantages</u>:
  - Maglev trains are quieter, faster and more energy efficient than conventional train systems.
    - Powerful electromagnets made from superconductors would use less energy than conventional electromagnets to keep Maglev trains suspended.
    - Currents can be produced and maintained with negligible heat loss.
  - The train does not make any physical contact with the track (no mechanical energy is lost to overcome friction), which minimises frictional drag, improves its maximum speed and minimises maintenance costs.
- <u>Disadvantages</u>:
  - Superconductors require low temperatures and huge amounts of electricity are needed to produce the strong magnetic fields required, so they are expensive to run.
  - Low temperatures are difficult to confine, and requires high technology.

3.4.11 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

- **Computers**
  - Typically, the speed and miniaturisation of computer chips are limited by the generation of heat and the speed of signal conduction.
  - Superconductors have the potential to create very fast switches for use in transistors in devices known as Josephson junctions.
- **Motors & Generators**
  - Motors and generators made using superconducting coils would be much lighter and smaller, as no iron core is needed.
  - Less energy input would be needed to sustain their operation, reducing energy requirements and costs and improving efficiency.
  - Reduced energy requirements would also require fewer fossil fuels to be burnt, reducing the depletion of non-renewable resources, air pollution and contributions to greenhouse effect.
- **Transmission of electricity**
  - Electrical transmission lines lose a large amount of energy due to the resistance of the wires.
  - If superconducting wiring was used, there would be no power loss, so a much more efficient distribution would be possible over extremely large distances, lowering the cost of power and removing restrictions on the proximity of population centres to generators.
  - Electricity could be transmitted in DC, at the ideal voltage, as transformers would no longer be required.

3.4.12 Perform an investigation to demonstrate magnetic levitation

- Aim: To demonstrate magnetic levitation.
- Equipment: superconducting plate inside a double-insulated bowl, liquid nitrogen, rare earth magnet.



- Method:
  - Initially, the magnet was lowered towards the superconductive plate at room temperature and observations were made.
  - Liquid nitrogen was poured over the plate, and the magnet was lowered down towards the plate again. Observations were made.

- Results:
  - If the temperature of the plate was *above* the T_C, the magnet did not levitate above the plate.
  - If the temperature was lowered using to liquid N_2 to *below* the T_C, the magnet levitated at a certain height above the superconducting plate. If the magnet was moved up or down, it always returned to that particular height above the plate.
- Discussion:
  - The levitation of the magnet above the superconductor was due to the principle of magnetic exclusion (Meissner effect). For a small light magnet, the repulsive force of magnetic poles is sufficient to balance out the weight force.
  - The magnet stays at one height due to Lenz's Law. If the magnet is moved closer to the superconductor, there is an increase in flux threading the plate, leading to increased flux induction. This causes an increased repulsive force, until the weight force balances out.
- Risk Assessment:
  - Liquid nitrogen can cause serious injury (freezing) if it comes into contact with skin or eyes.
    - This experiment should be a teacher demonstration, and students should stand some distance away. Thick insulative gloves, safety glasses and a lab coat should be worn.