

Module 3: Ideas to Implementation

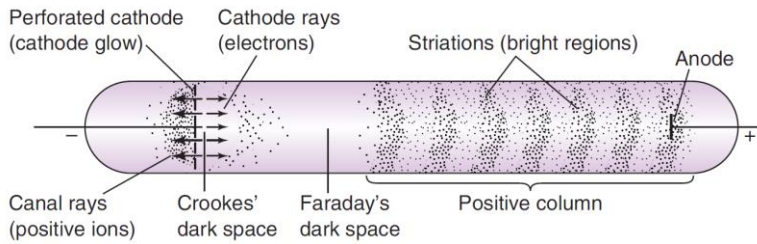
1. Increased understandings of cathode rays led to the development of television.

Students learn to:

Scientist/ Year	Relevant Observation	Conclusion/ Impact
1858 – Plucker	Magnets affected the discharge path.	They are electrically charged.
1875 – Crookes	Maltese cross, paddle tube, bent tube, etc. experiments.	Travel in straight lines, aren't penetrating, have momentum.
1883 – Hertz	Showed that cathode rays were not deflected by charged plates.	This suggests that they were waves.
1885 – Perrin	Cathode rays increase the divergence of negatively charged leaves on electroscope.	They are negatively charged.
1886 – Goldstein	Identified 'canal rays'. Disproved Hertz, showing rays deflected toward positive plate.	Supports negatively charged particles.
1890 – Schuster	Calculated the charge to mass ratio of cathode rays.	Too small to be ions, the smallest thing known then.
1892 – Hertz	Could penetrate thin metal foil.	Wave property.
1892 – Lenard	Predicted their velocity to be c .	EM wave property.
1894 – Thomson	Proved cathode rays travel 2000 times slower than c .	Puts in doubt wave theory.
1895 – Perrin	Cathode rays left a negative charge on impact.	Supports charge/ particle theory.
1897 – Thomson	Measured the mass of cathode ray particles as 1800 times less than H^+ .	Suggested they were electrons.

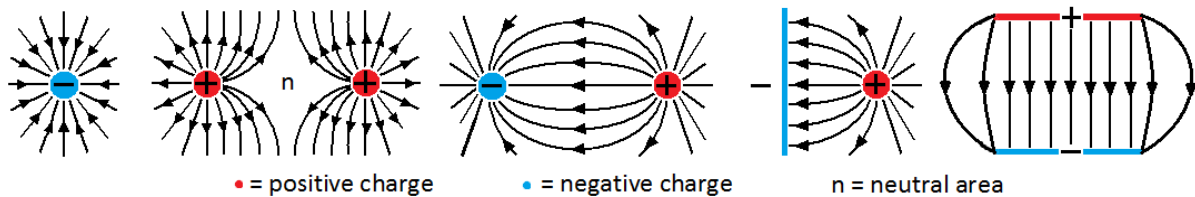
- Many scientists, of which the above are just a few, **investigated cathode rays**. However the cathode rays produced by the discharge tubes were a mystery because they **appeared to show properties of both waves and particles**. The main features are shown below. This originally led to the conclusion that **cathode rays were electromagnetic waves**; drawn due to **inadequacies in experimental procedure**, like Hertz's, and the atomic model. However as technology developed and more experiments were done, they were **eventually confirmed to be particles**, albeit with wave like characteristics.
- With the development of the **vacuum pump** and the **induction coil**, the construction of **cathode ray discharge tubes** occurred. Cathode rays are **streams of electrons or charged particles** ejected from the **cathode towards the anode** under high voltage (kV) in highly evacuated glass tubes. They interact with air in different ways **depending on pressure**, as below, requiring low pressures to be generated at all. Discharge tubes allow these **streams of charged particles to be**

Properties of particles	Properties of waves
They have momentum and hence mass.	Predicted velocity was the speed of light.
Measured velocity is 2000 times slower than the speed of light.	Predicted mass was too small for any particle known.
Left a negative charge after impact on an object.	Exposed photographic plates and caused fluorescent glow.
Rays left the cathode at right angles.	They travel in straight lines and could penetrate thin foil.



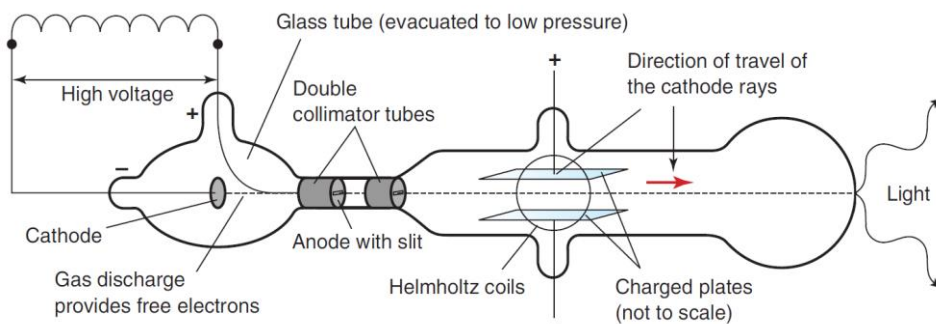
manipulated, using **external electric or magnetic fields**, etc. to be established outside the tube to affect the rays or building tubes with **apparatus inside** the tubes to create differing experiments.

- A **moving charged particle** experiences a **force** when placed in a **magnetic field**. The direction of this force is always **perpendicular** to the direction of movement, as dictated by a hand rule. If the particle is **positively charged**, the direction is the same as conventional current, it is still a **right hand rule**. However if it is negatively charged, the **direction is reversed** and it becomes a **left hand rule**. Examples are a current, moving positive charges, and cathode rays.
- **Electric fields** cause forces on electrically charged objects and are **vector fields**, studied in the Preliminary course. Thus, **charged plates produce an electric field**, demonstrated below.
- The **magnitude of the force** effected on a charge moving through a field is given by $F = qvB \sin \theta$. Thus the magnitude of the force is **directly proportional** to the charge and velocity of the particle and the strength of the magnetic field, and **sinusoidally proportional** to the angle to the field vectors. Thus, if the **velocity is parallel** to the field, there is **no force**.
- **Electric fields** are best represented diagrammatically. They are defined as the **force experienced on a positive point charge** or positive test particle. The **arrows indicate the direction of the force** and the **spacing of the lines indicate the strength** (i.e. the closer together, the stronger the force).



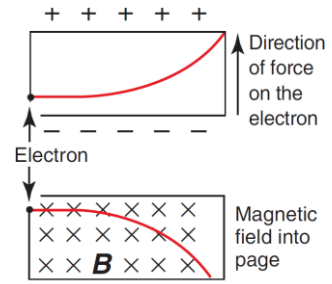
Thus, for a point charge the **field lines radiate out**, indicating a stronger force closer to the particle. Positive and negative charges interact in different ways, two of the same charge **cancel each other out** between leaving a neutral area while two of **differing charges combine**, as shown above. Two **oppositely charged parallel plates** establish a **uniform electric field** in between the plates. Interestingly, the plates have to be close enough to interact which means that the field on the other side of the plate, outside, is **neutralised** by the other plate. This means that there is only an electric field between the two plates, nothing outside.

- Two plates can become **oppositely charged** when a **potential difference** or voltage is applied across them, forming an **electric field**. The **magnitude of the field strength** is given by $E = \frac{V}{d}$ where E is the electric field strength, V is the voltage applied and d is the distance between the plates.
- **J. J. Thomson** conducted an experiment that was able to determine the **charge to mass ratio of the electron** (although it wasn't yet discovered, he suggested it as a new particle). His setup was thus: he used a typical **evacuated glass tube** or **discharge tube**, but turned the anodes into **double collimator tubes**.



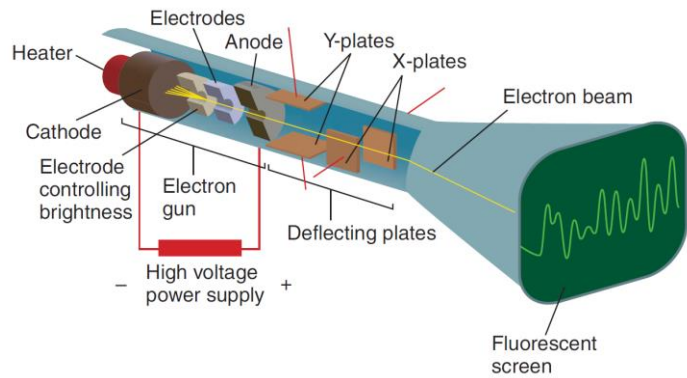
This focused the cathode ray into a thin beam. This beam was then passed between two parallel charged plates (**capacitor plates**), thus forming a

uniform electric field, and simultaneously through a **uniform magnetic field**, generated by **two current carrying coils**. This established a magnetic and an electric field that were **perpendicular** to each other, thus both producing a force which cancelled the other out, as shown right. The deflected electrons hence continued and impacted on a **fluorescent screen** at the end of the bulb, emitting light. By adjusting the strengths of the magnetic and electric fields, the beam can pass **undeflected**. By then equating the **magnetic and electric force equations** ($Eq = qvB$) the **velocity of the cathode rays** can be determined. He then removed the electric field entirely leaving the **same strength magnetic field** and measured the **radius of the circle of deflection**. By the equating the **magnetic force** and the **centripetal force** ($qvB = \frac{mv^2}{r}$), Thomson could calculate the **charge to mass ratio** of the electron ($\frac{q}{m} = \frac{v}{Br}$).



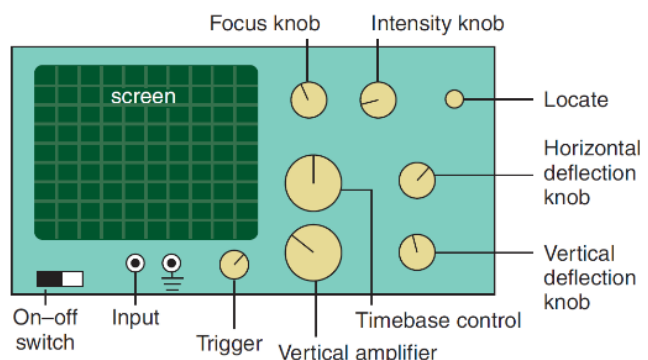
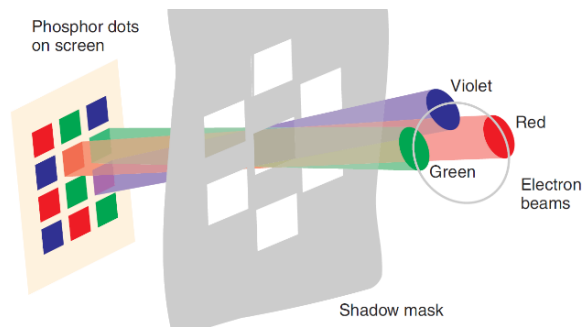
- For a **Television** or **Cathode Ray Oscilloscope (CRO)** to utilise cathode rays, it uses three main parts:

- In the **electron gun**, a **heating filament** heats the cathode to help release electrons via **thermionic emission**. The electrodes have an **extremely high voltage** passed through, as required by cathode rays, which accelerates them to the high speed required to excite the phosphor. The **density of electrons** determines the brightness of the image.



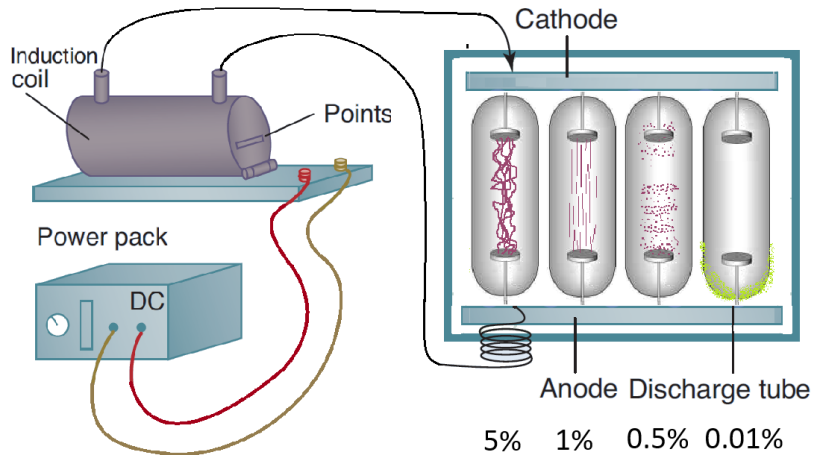
- Once the electron beam is **focused** and through the **anode**, there are two sets of **parallel deflecting plates**, electrically charged such that an **electric field** can send then beam to any **coordinates** on the screen. These direct the beam to the appropriate place on the screen.
- When the electron beam reaches the **fluorescent screen**, the **high energy electrons** interact with the fluorescent material and emit light. This allows the **position** of the ray to be seen.

A **Television** has **three different** electron guns, each aimed for a different **primary colour** of light, red, green and blue. When the beam hits the **fluorescent screen**, each beam hits an individual fluorescent that produces that colour, thus the beam transforms into a beam of light of said colour. The **shadow mask** is used to focus the light beams together on the screen making a **pixel**. In a standard CRT TV, the picture is refreshed at around **60 Hz**. A **CRO** enables individuals to plot **any wave function or pulse**, most commonly used on **electrical currents** and **sound waves**. The Y deflection plates control the displayed **amplitude** of the wave, or the voltage. The X deflection plates control the **sweep** or **time base**, which enables voltage to be plotted as a function of time.



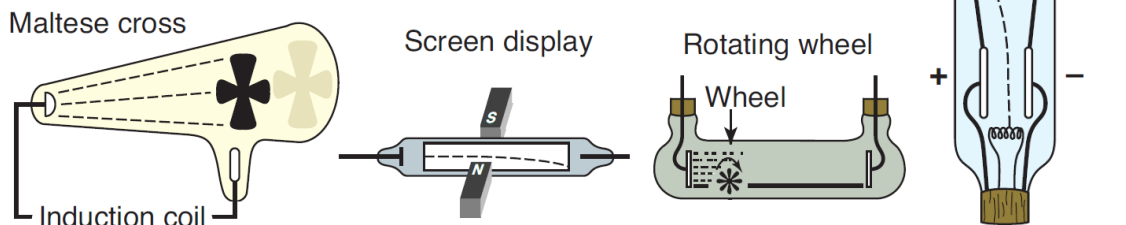
Students:

- **Practical Investigation – CRTs and Pressure.** Aim: to investigate the occurrence of different striation patterns under different pressures. **Independent Variable** – pressure in CRT; **Dependent Variable** – striation pattern. **Method:** acquire a CRT board, as right, which has different



pressured CRTs. Connect at DC current to an induction coil in the order of kV to then connect it the CRT board. Different striations should be visible depending on pressure. **Results:** as in diagram. At 5% atm, **reddish purple crackling lightning appears**; at 1% atm, **thin streaks appear**; at 0.5%, the **positive column appears** featuring **striations** at 0.01%, all **patterns disappear** and only a **green fluorescent glow** at the end of the tube remains.

- **Practical Investigation – Properties of Cathode Rays.** Aim: to determine some of the properties of cathode rays using Crooke’s discharge tubes. **Independent Variable** – different discharge tube; **Dependent Variable** - the property displayed. **Method:** attach high voltage as above to the four different discharge tubes, the Maltese cross, the fluorescent display screen, the glass wheel, and the electric plates. **Results:** from the **Maltese cross** as a sharp shadow is created, we can deduce that cathode rays travel in straight lines and they are not penetrating. From the **fluorescent screen** we can deduce that they are significantly energised to excite fluorescent material, therefore must have energy. From the **glass wheel**, the cathode rays make it turn thus must have momentum and hence mass, but also they are ejected from the cathode. From the **electric plates** we can deduce that cathode rays are negatively charged.

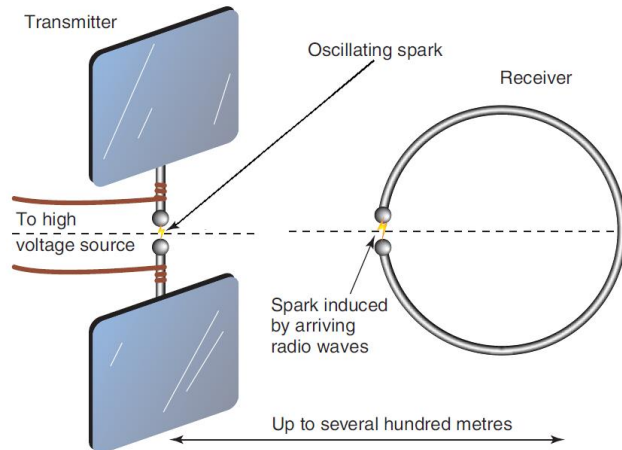


2. The reconceptualisation of the model of light led to an understanding of the photoelectric effect and black body radiation.

Students learn to:

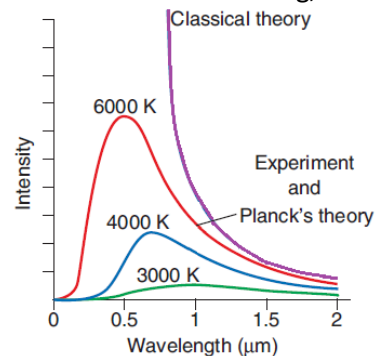
- In 1886, **Heinrich Hertz** conducted a series of experiments to **empirically confirm** Maxwell’s equations of light, in particular, the prediction of a **spectrum of electromagnetic radiation**. He observed when he **produced a radio wave**, as below, that the **receiver coil generated a spark** the same as the transmitter, thus electrically reflecting the transmitter. He noted that when he **shone the waves** from his transmitter directly into the spark gap, it could be **widened** and still produce a spark. However his transmitter was producing more than just radio waves and what he didn’t realise was his spark gap was **absorbing UV radiation** which, via the **photoelectric effect**, made it easier for the sparks to jump.

- **Hertz** constructed a **transmitter** and connected to an **induction coil** which enabled **quick sparks** to be transmitted, as pictured right. He then established a **receiving coil** which could be established up to several hundred metres away. This coil also **produced a spark** when the transmitter sparked, despite it being electrically independent. Moreover, the spark **appeared at the same time** in both devices. This was the first production of **radio waves**, later identified. In further experiments, he proved that the rays produced **interfered** with each other, **reflected**, **refracted** and could even be **polarised**; all characteristics of light. He was able to **calculate their velocity** using **interference patterns**. He used **Lloyd's mirrors**, setting up two beams; one that travelled directly to the source and one that was reflected after being emitted at a small angle. From the interference pattern produced, Hertz could calculate the wavelength and when combined with a known frequency using an **oscillating circuit**, the velocity could be calculated from the **wave equation**. Ultimately it was determined to be c , the speed of light. Undoubtedly, Hertz had proven there was an **electromagnetic spectrum**.



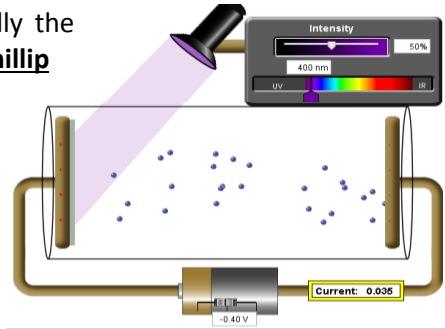
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- A **black body** is an object that will **absorb all radiation falling on it**. According to **thermodynamics**, as the temperature increases in the black body, whether from external radiation or heating, then it will **reradiate radiation across the entire spectrum**, each wavelength varying in intensity. Scientists constructed black bodies by creating an **induction furnace** with a **small hole** in it. As radiation was emitted as the furnace heated, it was forced to reabsorb the radiation, thus establishing an **equilibrium**. The radiation then exiting the hole was black body for a certain temperature, as right. Classical wave theory predicted an **infinite reaction** which contradicted the conservation of energy. **Max Planck** proposed that instead of energy being exchanged between the black body and the radiation emitted in one **continuous equilibrium radiation field**, it was instead exchanged as discrete **quanta** of energy. I.e. the interaction is **particle on particle**, not wave on particle. He described the energy of this quanta as $E = hf$, where $h = 6.626 \times 10^{-34}$ is **Planck's constant**. Planck did not believe his model accurately described reality, rather that it was merely a mathematical trick. However his quantisation of energy was the beginning of quantum theory.



- **Albert Einstein** capitalised on Planck's theories and suggested a **particle nature of light** in his 1905 paper (for which he won the Nobel Prize), using the **Photoelectric effect** as one example. He said that the **quanta of energy** that Planck described was called a **photon**, the smallest indivisible amount of radiation possible, described below. However technology wasn't good enough to prove his predictions (again) and it wasn't until 1916 that **Robert Milikan** begrudgingly provided the evidence, although he didn't believe Einstein.
- The **particle model of light** dictates that it travels through space as a **procession of discrete energy bundles** called **photons**. A photon is the smallest **indivisible amount of radiation possible**. As a particle in interactions, a photon could donate all of its energy or none, nothing in between. Its energy is discrete and is directly **proportional to its frequency**, as below. It also has a rest **mass of zero** and always travels at c .
- The above relationship expressed mathematically is $E = hf$, where $h = 6.626 \times 10^{-34}$. As all light travels at c , the wave equation can also be used, $c = f\lambda$. Go and solve problems my precious!

The Photoelectric Effect: The photoelectric effect is essentially the **emission of electrons** by shining a **beam of light** on a metal. **Phillip Lenard**, an assistant of Hertz, first conducted experimental investigations into the photoelectric effect in 1900. He found that light of a **particular frequency** exposed to an electrode in an **evacuated tube** caused electrons to be ejected, as right.



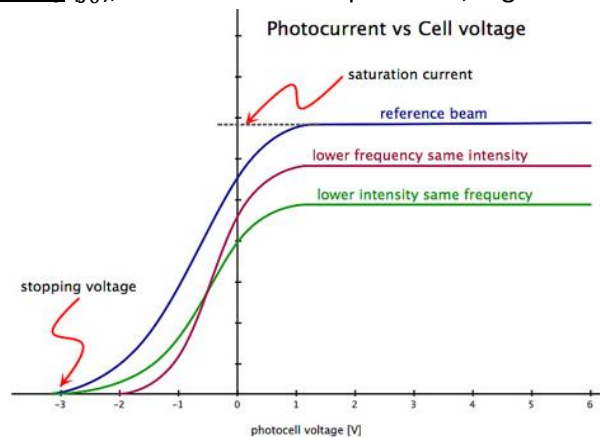
His other observations follow (represented graphically below):

- ◇ As the intensity is increased, the **current flowing increases**.
- ◇ With increased intensity, the **energy of the electrons does not increase**.

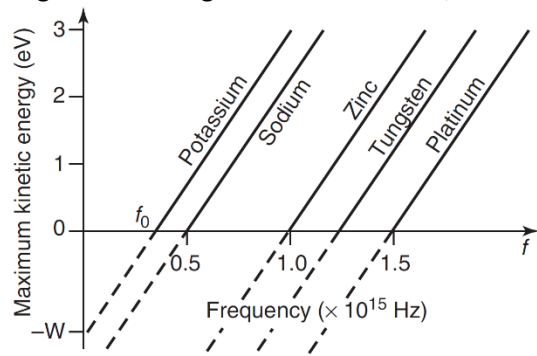
- ◇ When an external voltage is applied, creating an electric field, if increased the photoelectric current increases to a **saturation current**. If reversed (opposing) the current decreases until a **stopping voltage** (V_0) is reached. This value varies for **different metals and frequencies**.
- ◇ If the frequency drops below a **threshold frequency** (f_0), then **no current** is produced, regardless of intensity. This varies for different metals.

This was explained using photons:

- ◇ **Individual photons** have a specific energy, $E = hf$, which is used to successfully **ionise the atom** in a particle collision, ejecting an electron.
- ◇ As each metal's ionisation energy varies, the energy required to ionise is known as the **work function** (W).
- ◇ Any excess energy is used as **kinetic energy**.
- ◇ Intense light was merely **more photons** with the same energy, thus only increased the number of electrons ejected as each **interaction was one on one**.
- ◇ If the photon energy was below the **threshold frequency**, then the individual photons **didn't have enough energy** to ionise and no current was produced.



The electrons were obviously ejected at all sorts of angles and energies from the lattice, so the ones that determine the **stopping voltage** are the electrons ejected most perfectly, at right angles and with the greatest kinetic energy. This **maximum kinetic energy** can be described as $E_{Kmax} = hf - W$ where W is the work function of the metal. At the stopping voltage, a special E_{Kmax} is derived, where $E_{Kmax} = qV_0$. Therefore E_{Kmax} is equal to the **stopping voltage in electron volts**. This only works at stopping voltage and describes energy of electrons that just don't quite get there. This maximum kinetic energy of photons is graphically represented right, with each line having a gradient of h as in the form $y = mx + b$.

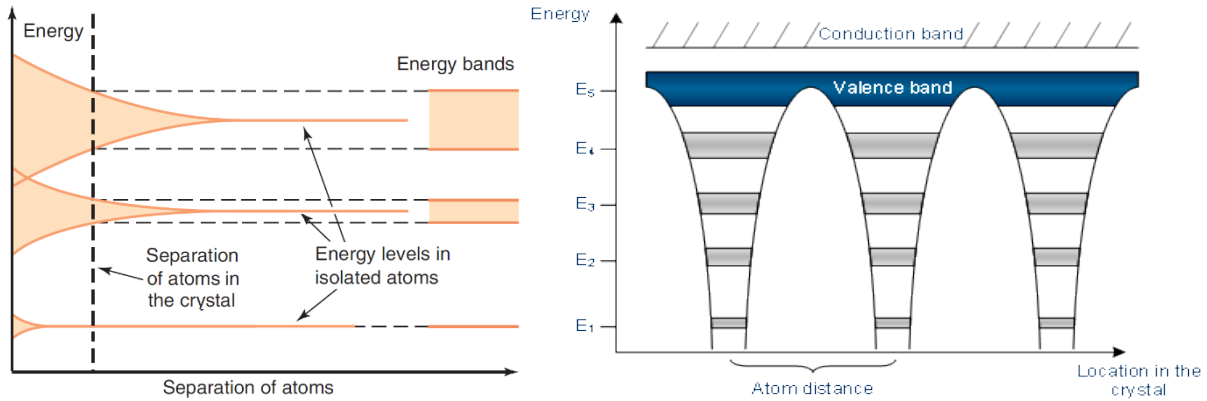


Students:

- **Practical Investigation – Radio Waves. Aim:** to demonstrate the production and reception of radio waves. **Independent Variable** – the distance from induction coil; **Dependent Variable** – whether the radio waves are received. **Method:** set up an induction coil such that the gap is approximately 5 mm (such induction sparks cause X-rays that are harmful, stand clear!) and insert a switch. Using a transistor radio not tuned to a station, find the maximum distance the radio waves can be heard (using switch to confirm with interrupted signals). Increase the spark distance and repeat. **Results:** the waves produced with each spark will be greater with greater distance as more energy will be released with a bigger spark. Hence the further the gap, the further away sound will be heard.

- Planck in 1900 invented the **fundamentals of quantum theory** when describing **black body radiation**, that the radiation from oscillating atoms (light) must be quantised. This is an example of **theory catching up to experiment**, the evidence for black body radiation curves were there, just they contradicted classical models. Hence Planck's work was crucial as it developed a new theory to explain the evidence. Einstein then developed and expanded this theory and assumed that since oscillating atoms producing light do so in a quantised form, and as all light must have a source, that **all light travels in quantised form**. He made detailed reference to the photoelectric effect, which was **qualitatively described by Philip Lenard** in 1900, as a way of **experimentally validating his theory**. The technology wasn't available to test his theories however in 1916, **Robert Milikan quantitatively proved** his theory correct. Thus Einstein expanded on the black body radiation theory and applied it to other areas with **testable predictions**, proving the **correlation between theory and experiment** and winning a Nobel Prize whilst at it. Not bad...
- A **photocell** is a device that **converts light energy into electrical energy**. It is used in many device such as photovoltaic cells, photoconductive cells and phototubes. All of these use **semiconductor technology** (p- and n-type junctions) to generate electricity, as described in the next dotpoint. However, when light hits the semiconductor, electrons are released due to the photoelectric effect and a **direct current** is established. This can be harnessed for the **actual voltage**, where focusing devices are used to generate an **efficiency of 37%** and is hence extremely useful allowing for the production of electricity wherever there is light. **Photoconductive cells** can measure the amount of light present by the current produced and can hence be used as alarms, light gates, in street lights, etc., anywhere where **light being blocked** results in an action. **Phototubes** are similar and are used as **electric eyes** to determine movement for automatic doors, taps, etc. Sensitive phototubes are also used to analyse the **radiation produced by celestial objects** for astronomers.
- Because of their **differing contextual backgrounds**, **Einstein and Planck** developed differing views about the **role of science in political and social contexts**. They had **much in common**, both were leading physicists, attended the same university and were German (although Einstein had Swiss citizenship). However Planck was a **conservative and proud Prussian** who as a high ranking scientist was a high public figure and hence nationally militaristic, and at the beginning of WWI signed the infamous "**Manifesto to the Civilised World**", a document promoting German military actions thus supporting the belief that it was the social right of a nation to take individual benefit of their scientific discoveries. Later Planck revoked parts of his manifesto. Einstein was **morally pacifistic** opposing any form of violence and hoped for a single global government, and hence responded to Planck's manifesto with a "**Manifesto to Europeans**" calling for peace. This supported Einstein's views that science was an activity to uplift all people and should be directed by social priorities. During Nazi rise to power, Planck first adopted a '**persevere and keep working**' philosophy however when the Nazis directly intervened in the Kaiser Wilhelm Institute, he **resigned as president**. Einstein meanwhile fled Germany due to **social persecution** of Jews, of which he was one, whilst still opposing German barbarism. However he temporarily **abandoned** his pacifistic stance to encourage **President Roosevelt** to build an **atomic bomb** in reaction to German political use of science. This was then misused by the Americans. He also **rejected the Presidency of Israel** to continue working in science, believing, along with Planck's final decision, that science was more useful when **applied socially fair** to **benefit all peoples** and **removed from political forces** which squander and horde knowledge.

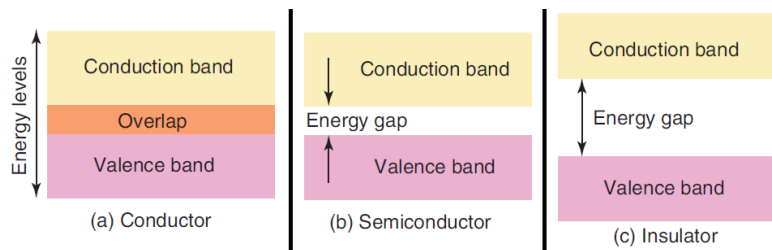




3. Limitations of past technologies and increased research into the structure of the atom resulted in the invention of transistors.

Students learn to:

- In some solids, the **outer electrons** of atoms in the intermolecular structure are **very loosely held** and free to be **shared between atoms**, hence forming a **sea of electrons** through the substance.
- In any substance, when atoms are **moved closer together**, interactions with other electrons in near atoms cause the **specific band energies of any given atom to diverge**, as in the graph right. Thus, when atoms are **bonded in solids**, electrons occupy **orbital bands** rather than specific orbital shells. Depending on the individual atomic bonding, this can result in the outermost band, the **valence band**, to **overlap** with the **conduction band**, where electrons are **delocalised completely**. In **insulators**, like ionic or covalent substances, the atoms are **strongly bonded** such that the forbidden energy gap between



the **valence and conduction band is big**, which causes a high electrical resistance as it take very large voltages to entice electrons into the conduction band. In **conductors**, like metallic lattices, the **valence band clearly overlaps** with the conduction band such that the majority of valence electrons are delocalised, thus giving it a very low electrical resistance and if the **bands overlap more**, than it is **less electrically resistive**. In **semiconductors**, there is a gap between bands however it is **small** and if the lattice is appropriately **excited** (usually though heat), then electrons will gain enough energy to jump up into the conduction band and become **delocalised**, thus giving it a medium electrical conductivity.

- In a **semiconductor**, when an electron jumps to the conduction band it **leaves a corresponding hole of positive charge behind**, i.e. the disappearance of the negative electron in the neutral band leaves a positive

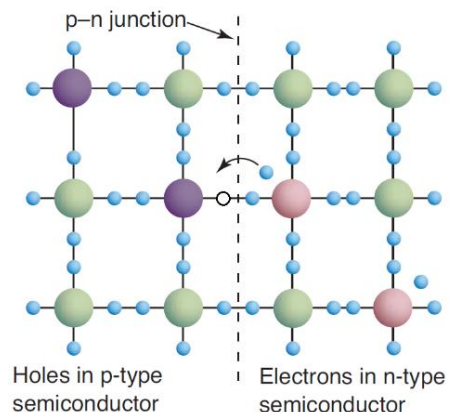
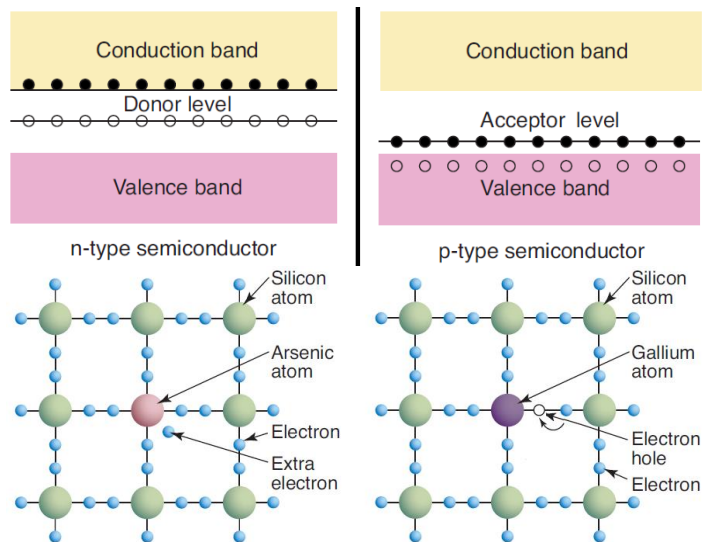
hole. This positive charge is then neutralised by surrounding electrons who in turn leave their own hole. Thus, the positive hole can be transmitted through the

	Conductor	Semiconductor	Insulator
Delocalised Electrons	Many, about 1 per atom.	Few, about one per billion atoms.	Zip, zero and zilch.
Resistivity vs Temperature	$\times 10^{-8} \Omega$	$\times 10^2 \Omega$	$\times 10^{15} \Omega$
			No conductivity

valence band and **conduct electricity** (flow of charge), although this flow is much slower in the electron zipping through the conduction band as it has to **individually visit every atom**.

- **Semiconductors** are most often **Group IV** semimetals who form in **tetrahedral lattices**. The two most common are Silicon and Germanium. **Germanium** was used first because in WWII, it was the only element they had the **technology to purify** to the required standards. Even small impurities or crystalline faults will drastically affect electrical conductivity. Thus Germanium was easier to work with and it also allowed for higher frequency electrical manipulation than silicon. However when it was heated ($>70^{\circ}\text{C}$) it became **too electrically conductive** such that the current would damage the electrical components. Germanium was also **very expensive** (\$1800/kg), **extremely rare** on earth and always found in **compound form**. Thus it was quickly replaced by **Silicon** because it is the second **most abundant element** on the earth (by weight) and hence cheap (\$2.5/kg), it retains its semiconducting properties at **high temperatures** (125°C), it can handle higher electric currents before overheating and destroying its semiconductor properties, its oxide can be made into **very flat layers and doped**, and the molecular structure results in **uniform properties**.
- **Doping a semiconductor** is the deliberate **addition of specific impurities** to enhance its semiconducting properties. It is achieved by adding a **group 3** or **group 5** element in small quantities to a pure semiconductor, say silicon. This **disparity in valence electrons** allows for the creation of an **extra energy level in the forbidden energy gap** which means that electrons require less energy to be excited into the conduction band, increasing conductivity. Only a **small amount** of dopant is required, one dopant in every 200,000 silicon atoms. Doping is achieved through various methods, like **diffusion**.

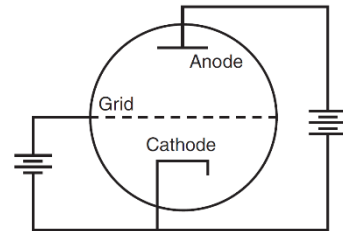
- There are two types of doping, p- and n-type. **P-type** is the addition of a **group three** element, like **Gallium** or **Boron**. This atom bonds into the lattice as shown left however with **one less valence electron** so it leaves a hole behind, a **hole of positive charge**, as before. This hole creates an **acceptor level** in the **forbidden energy gap** such that electrons who fill it require less energy to then be excited to the conduction band, thus increasing its electrical conductivity. Because the **ratio of holes to electrons** is **greater** than a normal semiconductor, it mainly uses **positive holes** to change its electrical properties, hence positive or p-type. **N-type** is the addition of a **group 5** such as **Arsenic** or **Phosphorus** that when bonded in the lattice, one **valence electron is left over**. This spare electron creates a **donor level**, not quite in the conduction band, but requiring very little energy to excite it, hence increasing conductivity. Because it uses spare electrons to change its properties, or **negative charge carriers**, it is termed negative or n-type.



The P-N Junction: is the special case when opposing doped semiconductors meet. The P-type has many acceptor atoms who will accept an electron to fill their positive hole. The N-type has donor atoms with spare electrons so the electrons from the N-type travel to the holes of the P-type and

neutralise. Due to the distribution of charge, this results in the P-type section having a negative charge and the N-type having a positive charge which establishes an electric field. Thus as the diffusion of electrons and holes continues, the field gets stronger until it repels the electrons and stops them from travelling any further. This forms a depletion zone with very few holes or free electrons, except for any randomly thermally generated exceptions.

- Thermionic devices** were used in electronics before solid state because they were the **only available technology**. They consist of **two or more electrodes** in an **evacuated glass tube**, very similar to CRTs, where if a negative voltage is applied to the cathode, then electrons will be emitted and current will flow. A simple **thermionic diode** operates because electrons cannot be emitted from the anode, hence voltage can only flow one way. This enabled for **rectification**, the ability to turn AC into DC, and when more electrodes are added as above, then the **amplification** and manipulating of alternating currents is also possible. However thermionic devices had many **problems**. They were **very bulky** so even simple devices were massive and not really portable. They also **require high voltages** to function and also create **massive heat loss** such that energy consumption was high. This heat required engineering solutions but also melted off the special metal which generated many electrons. They were also **very fragile**, being made of glass and requiring a vacuum, and hence had a **very short life time**, requiring constant maintenance. **Solid state devices** have none of these problems. They are constructed **using P-N Junctions** and **semiconductors** and can perform all the tasks of thermionic devices. A standard junction acts as a diode alone, the electric field resisting and assisting electric current such that current can only flow one way. Solid state chips can also be processed **much more cheaply** and in **larger volumes** and be constructed **much smaller than valves**. Thus solid state replaced thermionic because of all the problems associated with thermionic and the advantages associated with solid state.

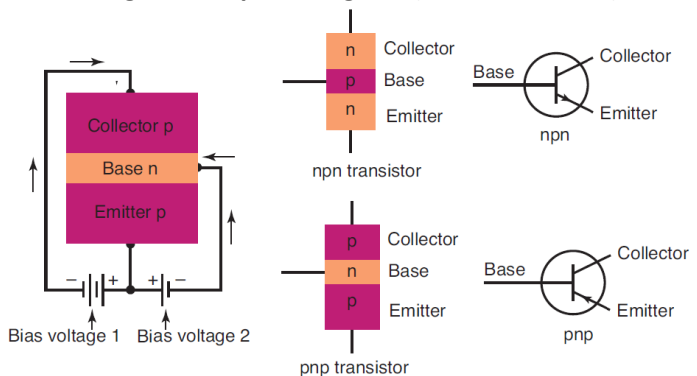


Students:

- Practical Investigation – Modelling a Semiconductor. Aim:** to model the behaviour of semiconductors. **Variables** – not applicable. **Method:** collect a piece of packing foam with indents and rises as depicted left, this represents the lattice of the semiconductor. Place marbles in all the indents, these represent the valence electrons. Now remove a few electrons, this represents a p-type semiconductor or where electrons have been excited to the conduction band. Alternatively add more marbles amongst the lattice, representing an n-type semiconductor. Now tilt the packing foam; holes or marbles will flow across the surface. This represents the application of an electric field to the semiconductor.

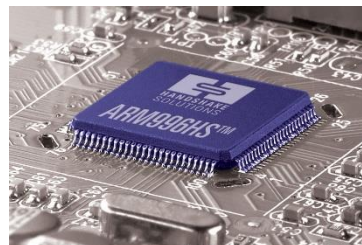


- Thermionic valves** were used in all **electrical communications** like telephone, speakers and radio. However the thermionic valves limited the **strength of amplified signals** (weak radio, etc.) and as well as that they had the problems listed above. This barrier **generated motivation** for research hence Bardeen and Brattain discovered voltage applied to Germanium was amplified. Shockley realised this potential and **comprehensively investigated semiconductor** properties which lead to the invention of the **transistor**. A

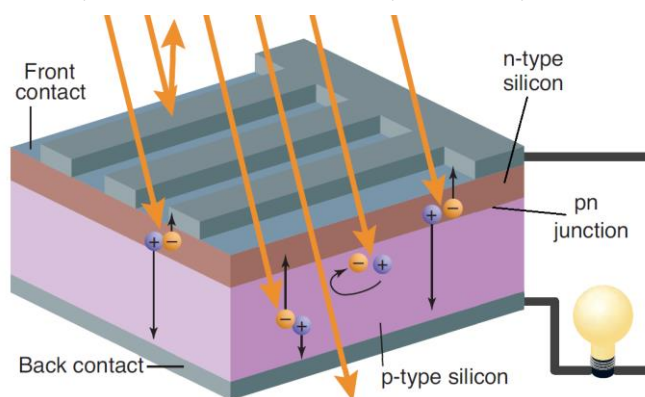


transistor is a semiconductor that can act as a **switch** or **amplifier** and is the combination of **two P-N junctions** in close proximity. The transistor consists of three regions; the **collector** and **emitter** are the same type whilst the **base** is opposite thinner. Each junction must be **correctly biased** for the transistor to function. When the bias to the base varies, they can vary the amplification and hence the signal strength produced, allowing it to also function as a switch; greater than this voltage, ON, less OFF.

- With the invention of **semiconductor transistors**, solid state soon replaced thermionic but only on a discrete level. Next came **integrated circuits**, tiny circuits made from silicon chips that can act like the larger thermionic systems however all of the **interconnections** are built into the chip so they are **self-contained units**. Some of the larger **microchips** today contain up to five million circuit components like transistors and resistors. These microchips are built up from **silicon wafers** (treated with other materials as well) three dimensionally constructed with projected light imprinting. The chips are assembled into **packages** containing all of the external connections to facilitate insertion into printed **circuit boards**. This enabled the **miniaturisation** of electronics and the possibility of **microprocessors**. This has had a massive impact on global society, all electronics uses these microchips which have enabled society to become much more efficient. They have improved **standards of living**, exponentially **increased communication**, made **military** more powerful, reduced **manual labour**, etc. Thus, transistors have led to a **massive global change**.



- **Photovoltaic Cells** are applications of the **photoelectric effect** and the **P-N junction**. When the junction is established, an **electric field** is also established throughout the cell acting like a **diode**. When **photons** arrive and **excite the electrons** in the semiconductor, the holes and electrons carry charge across the junction. When the junction is connected to a **metal contact grid** it acts as a **terminal** such

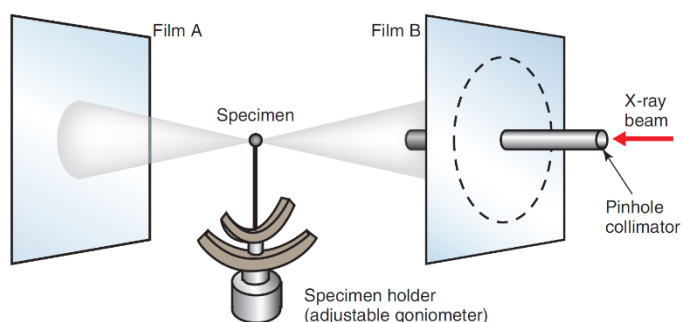


that the electrons can escape through a **circuit** and **perform work** on some load. If the grid is large, it reflects light but has decreased resistance. Thus, there is a trade. Once they complete the circuit, they nullify the holes awaiting for them. Thus the energy of the photons is **transformed** into electrical energy. To **increase voltage or current** multiple cells are connected in parallel or series.

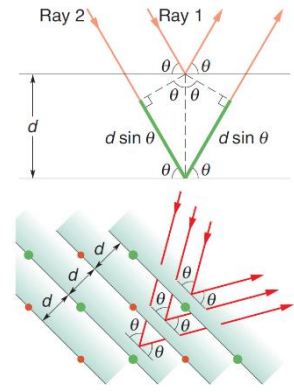
4. Investigations into the electrical properties of particular metals at different temperatures led to the identification of superconductivity and the exploration of possible applications.

Students learn to:

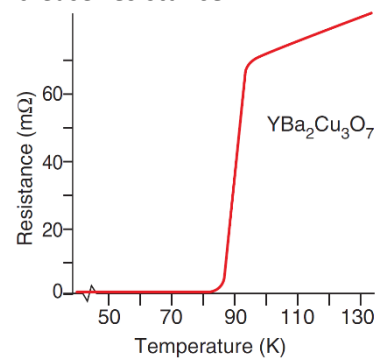
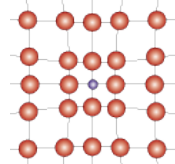
- Two scientists, **William Henry Bragg** and his son **William Lawrence Bragg** studied the phenomena of the **scattering of X-rays caused by crystal lattices**. The discovery of X-rays by Roentgen in 1895 was necessary for the Braggs experiment as the **diffraction of waves** necessary for scattering only occurs when the



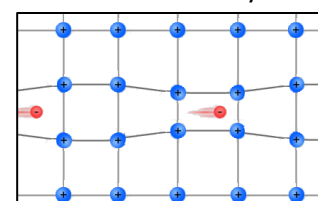
wavelength of the wave is about the **same size as the gap** it is passing through and as X-rays have **significantly shorter wavelengths** (10^{-10} m) than anything discovered before it made the diffraction patterns possible. The Braggs aimed **X-rays at crystal structures** and observed the **interference patterns** produced on a **photographic film**. By analysing the interference patterns with **geometry**, the exact **crystal structure** of the substance could be determined. To produce the X-rays, they impacted high energy electrons into copper or chromium which ejected X-rays in return. They then made the **X-rays parallel** using a collimator lined with molybdenum. The explanation following is an extreme simplification. As the X-rays **impacted the surface** of the crystal, they were **reflected at various depths** by differing crystal layers. As they were parallel, the X-rays emerged parallel however some had **travelled further**, as shown above. This produced an interference pattern from which the distance between **crystal layers** could be determined and hence the **entire crystal modelled**. This technique, and the associated mathematical law known as Bragg's Law, was used by many after to study the structure of substances and helped with the discovery of DNA, transistors and microchips. The Braggs won a Nobel Prize for this work in 1915.



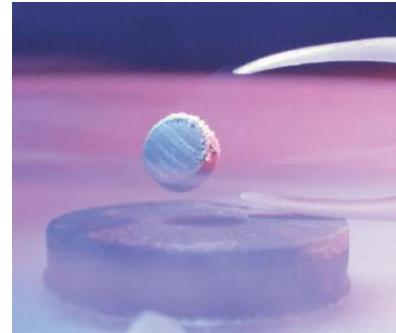
- When **solid metals** are formed, the molecules arrange themselves in an **ordered geometrical pattern** producing a **uniform crystal lattice**. This was hypothesised but **Bragg Crystallography** was able to confirm the theory, including the fact that in a metal lattice the individual atoms are close enough such that their **valence electron shells overlap** and **delocalise** the electrons.
- In an **ordinary lattice**, the **delocalised electrons** are moving in **all directions** at **high velocities**, however there is **not net charge movement** as it is **purely random**. However when an **electrical potential or field** is applied, the electrons come under force and thus, although the movement is largely random, the net movement or **drift velocity** is directly proportional to the voltage applied otherwise known as **current**. The greater the **cross section** of the metal, the more electrons are able to move, the greater current can be applied. Thus, **conduction** in a lattice is the **free movement** of delocalised electrons largely **unimpeded by the lattice**.
- Some **collisions** and **interactions** between ions and other electrons **generate heat** in the lattice, i.e. **further lattice vibrations**. Thus, the more a **lattice vibrates**, the greater chance of **electron collision** or **electron scattering** and hence **energy loss**. When the **current is steady**, all the energy lost is used in increasing lattice vibrations, i.e. **resistance** or **joule heating**. The presence of **impurities** or **imperfections** in the lattice greatly increase the chance of **electron collision** and thus increase **resistance**.
- **Superconductivity** is the occurrence of near **zero resistance** at **cold temperatures**. When superconducting, the electrons pass **perfectly unimpeded** through the lattice with **no collisions**, thus no heat or resistance. This is possible due to the formation of electron **Cooper pairs** which interact with each other and the lattice to **eliminate resistance**.



- From the discovery of **superconductivity** in 1911 it took 46 years to come up with a theoretical explanation that relies on **quantum mechanics** anyway. This is called **the BCS theory** (after its inventors, Bardeen, Cooper and Schrieffer) and is useful to observe the meaning of a model in science. The BCS theory relies two main concepts, **phonons** and **Cooper pairs**. A **phonon** is **quantum of lattice vibration**. Due to the extremely cold temperatures, phonons are mainly produced by **interactions with electrons**. From a **classical** point of view, electrons can pair together in **Cooper pairs** that are **constantly breaking and reforming** such that when travelling through a still lattice, the **Coulomb attraction** between the lattice and electrons causes the **lattice to bend in**



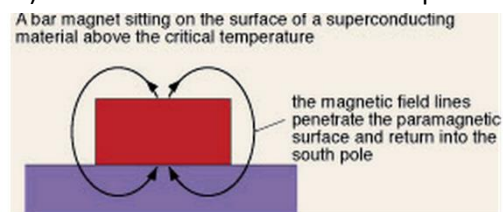
towards the electrons generating a phonon, as right. The **contraction** of the lattice and mass of positive charge attracts the electron behind, **pulling it forward** and hence absorbing the phonon. Thus, **zero resistance** is achieved. However this model breaks down because to be close enough to exchange phonons, the Cooper pairs would also repel each other, amongst other issues. Instead, **quantum mechanics** can be considered. To reach a **lower energy state**, an electron can be cooled such that it jumps down an **energy gap** (although still independent). To jump back up again and **destroy the superconducting** effect requires **significant energy input** (equal to T_c) so the electrons are stable here. Once here it can form a **Cooper pair** with another electron of **opposite spin** (refer to Quanta to Quark). By exchanging **phonons** from distance, the electrons combine spin such that instead of acting as a **fermion** (spin $\pm \frac{1}{2}$) they can act as a **boson** (integer spin). This means they no longer obey **Pauli's exclusion principle** and hence all electrons can condense to the **lowest energy state**. Thus, **millions of Cooper pairs** could occupy the same space without **overlapping** and could hence **assist** each other to move through the lattice unimpeded. This also allowed **Cooper pairs** to be formed over **large distance** travelling in **different directions**. This quantum mechanical explanation solved all the problems associated with **metallic (Type I) superconductors** however could not explain the **ceramic (Type II) superconductors** whose T_c was much higher (in fact there still is no explanation). This is a good example of **two different models** that explain the **same thing** to differing degrees of **accuracy**.



- The most obvious advantage of **superconductors** is their **lack of electrical resistance**. This means **no energy loss** when electrical currents are passed through and can use **thinner wires** to no detriment which is useful for **economic power storage and transmission**. Through the **Meissner Effect**, they can generate **extremely powerful magnetic fields** per unit weight which is useful for **motors and generators, MRI and maglev trains**. However they have a **maximum current** (fixed for each superconductor regardless of shape) that can be applied before properties are lost, which limits some uses. They are also **very expensive** to keep below the **critical temperature** which **counters their economic advantages** in most cases. Type II superconductors are raising this limit to rates for cooling by **liquid nitrogen** (much cheaper) however these are difficult to produce, chemically unstable, brittle, and non-ductile which limits even their uses. Thus superconducting technology **needs significant improvement** to become **economically effective** in many situations.

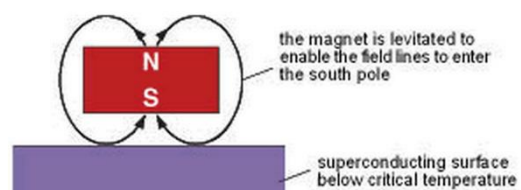
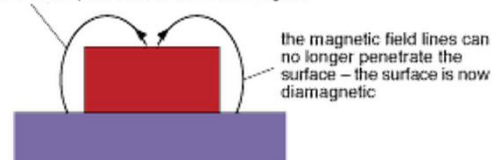
Students:

- An example of **magnetic levitation** is the **Meissner effect**. Immerse a high T_c superconductor in **liquid nitrogen** such that it becomes superconductive and hold a **rare earth magnet** over the superconductor as pictured below. The magnet will interact with the superconductor to cause **magnetic levitation**.
- The **Meissner Effect** is the property of all superconductors to **expel magnetic fields**. When a superconductor is placed in a magnetic field, the magnetic field will **induce a current** within the superconductor. This current induces a magnetic field that is **exactly opposite in direction** to the



A bar magnet sitting on the surface of a superconducting material at the critical temperature

the inability of magnetic field lines to enter the south pole causes lift of the magnet



external magnetic field as there is no energy lost in the induction, thus cancelling the field and expelling all magnetic flux from the superconductor. These are **not eddy currents** as they require relative motion whereas once the current is established, it will infinitely flow with no change in flux. If the external field changes, the currents will change to match. As all **flux lines must flow from a north to a south uninterrupted**, the magnetic field will be forced to bend and strengthen around the superconductor as a result and thus **allow for levitation**, the magnetic field will become strong enough to cancel gravity.

- **Maglev Trains** are trains suspended by **magnetic levitation**. This enables **no contact with solid surfaces** where the only frictional resistance is air resistance reaching speeds of 517 kmh⁻¹. The **electrodynamic system** (EDS) used in Japan has **superconducting electromagnets**

<i>Superconductor</i>	<i>Compound</i>	<i>T_c (K)</i>
Mercury (Mg)	Metal	4.2
Lead (Pb)	Metal	7.2
Vanadium Silicate (V ₃ Si)	Alloy	16.9
Niobium Aluminate (Nb ₃ Al)	Alloy	18.7
Yttrium-Barium-Copper Oxide (YBa ₂ Cu ₃ O ₇)	Ceramic	92
Thallium-Barium-Calcium-Copper Oxide (Th ₂ Ba ₂ Ca ₂ Cu ₃ O ₁₀)	Ceramic	125

where the zero resistance and infinite current enable **extremely strong magnetic fields** to be produced. Electrically conductive strips are laid on the track which induce **opposing magnetic fields** to enable levitation. The propulsion system uses **alternating electromagnets** to produce a constant repulsion/attraction action to accelerate the train. They are **currently impractical** due to the enormous electrical requirements to maintain superconductivity.

- The applications of superconductors are practically ultimate, including:
 - **Computers:** the current size and speed of microchips are limited by the production of heat and conducting speed. Superconductive film would result in more densely packed transistors and reduce the processing time by several orders of magnitude. Thus there is massive potential for applications in electronics and computing.
 - **Motors and Generators:** with the use of superconductor electromagnets, the current stator magnets could be reduced to a fraction of the size for the same power and would remove the need for iron cores to increase the efficiency. Thus, superconductors would enable motors and generators to be more powerful, smaller and more efficient.
 - **Electrical Transmission:** if high temperature superconductors could overcome their current brittleness, then new thin wires could carry 3 to 5 times the current which would reduce line loss cost and metallic wire cost. A current problem is of peak consumption. Because electrical energy cannot be stored, power stations must produce electricity at peak consumption 24/7. Superconducting magnetic energy storage (SMES) allows for electrical energy to be stored in superconductors where the current runs infinitely without energy loss. Thus stations could produce energy at average consumption and still provide the required energy which would vastly reduce energy costs.