Physics Summary

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Core Topic One: Space

1. The Earth has a gravitational field that exerts a force on objects both on it and around it

§ Define weight as the force on an object due to a gravitational field

The **weight** of an object is the force of gravity acting on it.

$$\vec{W} = m\vec{g}$$

Where W is the weight in newtons (N), m is the mass in kilograms (kg) and *g* can be either:

1. The *acceleration due to gravity* (= 9.8 m/s/s at the Earth's surface); or
2. The *gravitational field strength* (= 9.8 N/kg at the Earth's surface).

§ Define gravitational potential energy as the work done to move an object from a very large distance away to a point in a gravitational field.

As we lift an object from the ground to a height above the ground we do work on it. This work is stored in the object as *gravitational potential energy*. For an object of mass *m* at a height *h* above the Earth's surface the gravitational potential energy *E* is given by:

$$E_p = mgh$$

However this equation is valid only when the object is near the Earth's surface.

The **gravitational potential energy** is a measure of the work done in moving an object from infinity to a point in the field. The general expression for the gravitational potential energy of an object of mass *m* at a distance *r from the centre of the Earth* (or other planet) is given by:

$$E_p = -G\frac{mM_E}{r}$$

Where *M* is the mass of the Earth (or other planet).

Newton's Law of Universal Gravitation

$$F = G\frac{m_1 m_2}{r^2}$$

where G is the universal gravitational constant.

The Gravitational Field

Surrounding any object with mass is a gravitational field.

$$g = \frac{Gm}{r^2}$$

Change in Gravitational Potential Energy

The change in potential energy of a mass m_1 as it moves from infinity to a distance *r* from a source of a gravitational field (due to a mass m_2) is given by:

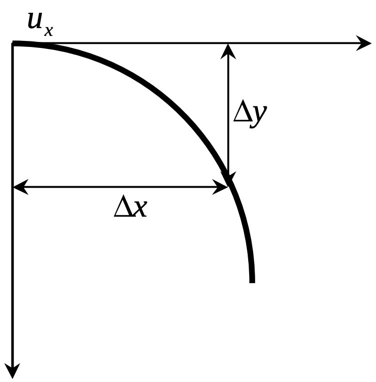
$$\Delta E_p = G\frac{m_1 m_2}{r}$$

Change in Gravitational Potential Energy Near the Earth (when radius increases from A to B)

$$\Delta E_p = GmM_E\left(\frac{1}{r_A} - \frac{1}{r_B}\right)$$

2. Many factors have to be taken into account to achieve a successful rocket launch, maintain a stable orbit and return to Earth

§ Describe the trajectory of an object undergoing projectile motion within the Earth's gravitational field in terms of horizontal and vertical components



$$\Delta y = k(\Delta x)^2$$

$$k = \left(\frac{a_g}{2u_x^2}\right)$$

Any moving object that moves <u>only</u> under the force of gravity is a projectile. The horizontal motion of a projectile is independent to the vertical motion. The reason for this result is that gravity is the <u>only</u> force acting on the objects and this always acts towards the centre of the Earth.

Projectile motion can be analysed by realising that:

1. The horizontal motion is **constant velocity.**
2. The vertical motion of **constant acceleration** (with acceleration of g).

Equations of Uniformly Accelerated Motion

$$\vec{v} = \vec{u} + \vec{a}t$$

$$\vec{s} = \vec{u}t + \frac{1}{2}\vec{a}t^2$$

$$v^2 = u^2 + 2as$$

The Path of a Projectile

The velocity at any point of the path of a projectile is simply the *vector sum* of the horizontal and vertical velocity components at that point.

The horizontal component is constant.
The vertical component changes at g, the acceleration due to gravity.

Trajectories

The path followed by a projectile – its **trajectory** – is a parabola (or linear)

(1) Horizontal motion: $\Delta x = u_x t$

(2) Vertical motion: $\Delta y = \frac{1}{2} a_g t^2$

From (1):

$$t = \frac{\Delta x}{u_x}$$

Combining (2) & (3):

$$\Delta y = \frac{1}{2} a_g \left(\frac{\Delta x}{u_x}\right)^2 = \frac{1}{2}\frac{a_g}{u_x^2}(\Delta x)^2$$

- Describe Galileo's analysis of projectile motion

Galileo was responsible for deducing the parabolic shape of the trajectory of a projectile. Galileo's analysis of projectile motion led him to consider *reference frames*. These are what all measurements are compared to.

The concept of Galilean relativity refers that the laws of mechanics are the same in a frame of reference that is at rest or one that moves with constant velocity.

- Explain the concept of escape velocity in terms of the:
  - gravitational constant
  - mass and radius of the planet

If an object is projected upward with a large enough velocity it can escape the gravitational pull of the Earth (or other planet) and go into space. The necessary velocity to leave the Earth (or other planet) is called the **escape velocity**.

Escape velocity depends on the gravitational constant, the mass and radius of the planet.

Suppose an object of mass *m* is projected vertically upward from the Earth's surface (mass of ***M*** and radius ***R***) with an initial velocity ***u***. The initial *mechanical energy*, that is, kinetic and potential energy is given by:

$$E_{k_i} + E_{p_i} = \frac{1}{2}mu^2 - G\frac{M_E m}{R_E}$$

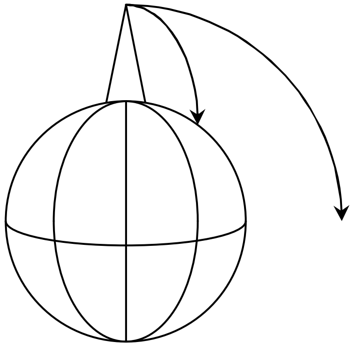
Let us assume that the initial speed is just enough so that the object reaches infinity with zero velocity. The value of the initial velocity for which this occurs is the escape velocity v_e.

When the object is at infinity the mechanical energy is zero (the kinetic energy is zero since the velocity is zero and the potential energy is zero because this is where we selected the zero of potential energy).

Hence $\frac{1}{2}mv_e^2 - G\frac{M_E m}{R_E} = 0$ which leads to:

$$v_e = \sqrt{\frac{2GM_E}{R_E}}$$

§ Discuss Newton's analysis of escape velocity

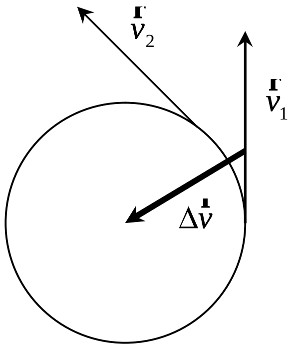


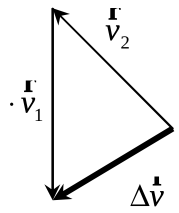
Isaac Newton proposed the idea of artificial satellites of the Earth. He considered how a projectile could be launched horizontally from the top of a high mountain so that it would not fall to Earth.

As the launch velocity was increased, the distance that the object would travel before hitting the Earth would increase until such a time that the velocity would be sufficient to put the object into orbit around the Earth. (A higher velocity would lead to the object escaping from the Earth.)

Circular Motion

The motion of an object in a circular path with constant speed is called **uniform circular motion.** Although the speed remains the same in uniform circular motion, it follows that an object travelling in a circular path must be *accelerating*, since the velocity (that is, the speed in a given *direction*) is continually changing. $\vec{v}_1 \neq \vec{v}_2 \qquad v_1 = v_2$





The change in velocity is given by:

$$\Delta\vec{v} = \vec{v}_2 - \vec{v}_1$$

and since: $\vec{a} = \dfrac{\Delta\vec{v}}{\Delta t}$

it follows that the object is accelerating.

Centripetal Acceleration

As can be seen, when the change in velocity is placed in the average position between v_1 and v_2, it is directed towards the *centre* of the circle. When an object is moving with uniform circular motion, the acceleration (the **centripetal acceleration**) is directed towards the centre of the circle. For an object moving in a circle of radius *r* with an *orbital velocity* of *v*, the centripetal acceleration ***a*** is given by:

$$a_c = \frac{v^2}{r}$$

Earth Orbits

A satellite can be put into Earth orbit by lifting it to a sufficient height and then giving it the required horizontal velocity so that it does not fall back to Earth. For the satellite to circle the Earth, the centripetal force required is provided by the gravitational attraction between the satellite and the Earth. Hence the centripetal acceleration is given by:

$$g = \frac{v^2}{R}$$

§ Use the term 'g forces' to explain the forces acting on an astronaut during launch

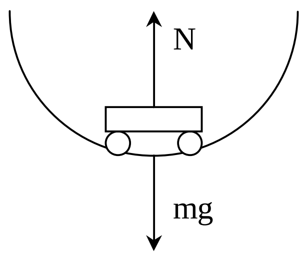
g-forces on Astronauts
Humans can withstand 4g without undue concern. Accelerations up to ~10g are tolerable for short times when the acceleration is directed parallel to a line drawn between the person's front and back.

The human body is relatively unaffected by high speeds. Changes in speed, however, that is, accelerations, can and do affect the human body creating ***'acceleration stress'***.

g-forces
Acceleration forces – g-forces – are measured in units of gravitational acceleration g. For example, a force of 5g is equivalent to acceleration five times the acceleration due to gravity.

If the accelerations are along the body's long axis then two distinct effects are possible:
1. If the acceleration is in the direction of the person's head they may experience a 'black out' as the blood rushes to their feet; or
2. If the acceleration is towards their feet, they may experience a 'red out' where the blood rushes to their head and retina.

§ Compare the forces acting on an astronaut during launch with what happens during a roller coaster ride



As you 'fall' from a height, you experience *negative g-forces* (you feel lighter). When you 'pull out' of a dip after a hill or follow an 'inside loop', you experience *positive g-forces* (you feel heavier). The positive g-forces are like those astronauts experience at lift-off.

Consider a rider in a car at the bottom of an inside loop. The rider has two forces acting on them:
1. Their normal weight (mg) acting down; and
2. The 'normal reaction force' (N) acting up. This is the push of the seat upwards on their bottom.

Assume that the loop is part of a circle of radius *R*. A *centripetal force* is required for the rider to travel in a circle. This is the difference between the normal force and the weight force, that is:

$$N - mg = \frac{mv^2}{R} : N = mg + \frac{mv^2}{R}$$

The *g-forces* are found from the 'normal force' divided by the weight. That is:

$$g\text{'s felt by rider} \quad = \frac{N}{mg} = \frac{mg + \frac{mv^2}{R}}{mg} = 1 + \frac{v^2}{gR}$$

§ Discuss the impact of the Earth's orbital motion and its rotational motion on the launch of a rocket

A moving platform offers a boost to the velocity of a projectile launched from it, if launched in the direction of motion of the platform. This principle is used in the launch of a rocket by considering that the Earth revolves around the Sun at 107,000km/h relative to the Sun and rotates once on its axis per day so that a point on the Equator has a rotational velocity of approximately 1,700km/h relative to the Sun. Hence, the Earth is itself a moving platform with two different motions which can be exploited in a rocket launch to gain a boost in velocity.

Earth Orbit
A rocket heading into orbit is launched to the east to receive a velocity boost from the Earth's rotational motion.

An Interplanetary Trip
The flight of a rocket heading into space is timed so that it can head out in the direction of the Earth's motion and thereby receive an extra boost.

§ Analyse the changing acceleration of a rocket during launch in terms of the:

Law of Conservation of Momentum

Forces experienced by astronauts

Law of Conservation of Momentum
Rocket engines generate thrust by burning fuel and expelling the resulting gases. Conservation of momentum means that as the gases move one way, the rocket moves the other. (Momentum before the burning is zero; hence the momentum after is also zero. The gases carry momentum in one direction down, and so the rocket carries an equal momentum in the opposite direction up.)

As fuel is consumed and the gases expelled, the mass of the system decreases. Since acceleration is proportional to the thrust and inversely proportional to the mass, as the mass decreases, the acceleration increases. Hence the forces on the astronauts increase.

Forces Experienced by Astronauts
g forces varied during the launch of *Saturn V*, a large three-stage rocket used to launch the *Apollo* spacecraft. This is attributed to the sequential shutdown of the multiple rocket engines of each stage – a technique designed specifically to avoid extreme *g* forces.

- Analyse the forces involved in uniform circular motion for a range of objects, including satellites orbiting the Earth

Motion	Fc Provided By…
Whirling rock on a string	The string
Electron orbiting atomic nucleus	Electron-nucleus electrical attraction
Car cornering	Friction between tyres and road
Moon revolving around Earth	Moon-Earth gravitational attraction
Satellite revolving around Earth	Satellite-Earth gravitational attraction

- Compare qualitatively and quantitatively low Earth and geostationary orbits

Low Earth Orbit

A low Earth orbit is generally an orbit higher than approximately 250 km, in order to avoid atmospheric drag, and lower than approximately 1000 km, which is the altitude at which the Van Allen radiation belts start to appear. The space shuttle utilises a low Earth orbit somewhere between 250 km and 400 km depending upon the mission. At 250 km, an orbiting spacecraft has a velocity of 27,900km/h and takes just 90 minutes to complete an orbit of the Earth.

Geostationary Orbit

A geostationary orbit is at an altitude at which the period of the orbit precisely matches that of the Earth. If over the Equator, such an orbit would allow a satellite to remain ‘parked’ over a fixed point on the surface of the Earth throughout the day and night. From the Earth such a satellite appears to be stationary in the sky, always located in the same direction regardless of the time of day. This is particularly useful for communications satellites because a receiving dish need only point to a fixed spot In the sky in order to remain in contact with the satellite.

The altitude of such an orbit is approximately 38,800 km. If a satellite at this height is not positioned over the Equator but at some other latitude, it will not remain fixed at one point in the sky. Instead, from the Earth the satellite will appear to trace out a ‘figure of eight’ path each 24 hours. It still has a period equal to the Earth’s, however, and so this orbit is referred to as geosynchronous.

§ Discuss the important of Newton's Law of Universal Gravitation in understanding and calculating the motion of satellites

Using Newton's Law of Universal Gravitation combined with the expression for centripetal force, we can see that the orbital velocity required for a particular orbit depends only on the mass of the Earth, the radius of the Earth and the altitude of the orbit (distance from the surface of the Earth). Given that the mass and radius of the Earth have fixed values, this means that altitude is the only variable that determines the specific velocity required. In addition, the greater the radius of the orbit, the lower the orbital velocity required.

Once a launched rocket has achieved a sufficient altitude above the surface of the Earth, it can be accelerated into an orbit. It must attain a specific speed that is dependent only upon the mass and radius of the Earth and the altitude above it. If that speed is not reached, the spacecraft will spiral back in until it re-enters the atmosphere; if the speed is exceeded, it will spiral out. This can be considered by appreciating that the simplest orbital motion is a uniform speed along a circular path around the Earth.

Uniform circular motion, as already mentioned, is a circular motion with a uniform orbital velocity. According to Newton's First Law of Motion, a spacecraft in orbit around the Earth, or any object in circular motion, requires some force to keep it there, otherwise it would fly off at a tangent to the circle. This force is directed back towards the centre of the circle. In the case of spacecraft, it is the gravitational attraction between the Earth and the spacecraft that acts to maintain the circular motion that is the orbit. The force required to maintain circular motion, known as **centripetal force**, can be determined using the following equation: $F_C = \frac{mv^2}{r}$

The application of Newton's **Law of Universal Gravitation** to the orbital motion of a satellite will produce an expression for the critical orbital velocity mentioned earlier. Recall that this law states that the gravitational attraction between a satellite and the Earth would be given by the following expression:

$$F_G = G\frac{m_E m_S}{r^2}$$

This gravitational force of attraction also serves as the centripetal force for the circular orbital motion, hence: $F_G = F_C$

Therefore, we can equate the formula for F_G with that for F_C:

$$G\frac{m_E m_S}{r^2} = \frac{m_S v^2}{r}$$

where
v = orbital velocity (ms^{-1})

$$\therefore v = \sqrt{\frac{Gm_E}{r}}$$

where
$r = r_E$ + altitude (m)

Kepler's Third Law:
The Law of Periods

Further, we can use the expression for orbital velocity to prove **Kepler's Third Law – the Law of Periods.** The period or the time taken to complete one full orbit can be found by dividing the length of the orbit (the circumference of the circle) by the orbital velocity, *v*.

$$T = \frac{2pr}{v}$$

Changing the subject of this expression to *v* and then substituting into the formula for *v* given above:

$$\frac{2pr}{T} = \sqrt{\frac{Gm_E}{r}}$$

$$\therefore \frac{r^3}{T^2} = \frac{Gm_E}{4p^2}$$

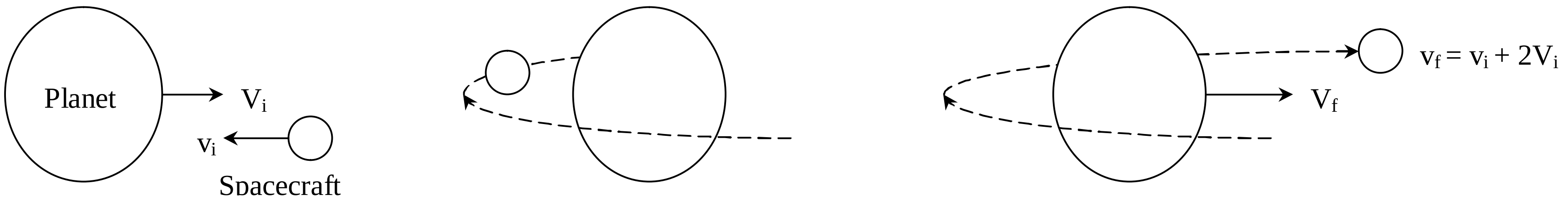
This means that for any satellite of the Earth at any altitude, the ratio $r^3{:}T^2$ always equals the same fixed value.

§ Describe how a slingshot effect is provided by planets for space probes

Many of today's space probes to distant planets such as Jupiter use a ***gravitational 'slingshot' effect*** (also known as a ***gravity-assist trajectory***) that brings the probe close to other planets to increase the probe's velocity. In 1974, *Mariner* 10 was directed past Venus on its way to Mercury. The *Pioneer* and *Voyager* probes also used this method.

Consider a trip to Jupiter such as the *Galileo* probe that involved a single fly-by of Venus and two of the Earth. As the probe approaches Venus, it is accelerated by Venus' gravitational attraction, causing it to speed up *relative to Venus*. (By Newton's Third Law, Venus will also experience a force slowing it down. It's mass, however, is so much greater than that of the probe that the velocity decrease is imperceptible.)

As the probe passes Venus, its speed is reduced (relative to Venus). Relative to the Sun, however, its speed has increased. The probe picks up *angular momentum* from the planet (which loses an equal amount of an angular momentum). Gravity allows the 'coupling' between the probe and planet to facilitate the transfer. For this reason, gravity-assist trajectories should more correctly be called *angular momentum-assist trajectories*.



§ Account for the orbital decay of satellites in low Earth orbit

All satellites in low Earth orbit are subject to some degree of atmospheric drag that will eventually decay their orbit and limit their lifetimes. As a satellite slows, it loses altitude and begins a slow spiral downwards. As it descends, it encounters higher density air and higher drag, speeding up the process. By the time the satellite is below an altitude of 200 km it has only a few hours left before colliding with the Earth. The re-entry process generates much heat and most satellites burn up (vaporise) before impacting.

§ Discuss issues associated with safe re-entry into the Earth's atmosphere and landing on the Earth's surface

There are significant technical difficulties involved in safe re-entry, the most important being:

1. The heat generated as the spacecraft contacts the Earth's atmosphere; and
2. Keeping the retarding-forces (*g-forces*) within safe limits for humans.

Heating Effects

The Earth's atmosphere provides *aerodynamic drag* on the spacecraft and as a result high temperatures are generated by friction with air molecules.

§ Identify that there is an optimum angle for re-entry into the Earth's atmosphere and the consequences of failing to achieve this angle.

***g*-Forces**

The angle of re-entry is critical: too shallow and the spacecraft will bounce off the atmosphere back into space; too steep and the *g*-forces will be too great for the crew to survive (and the temperatures generated with the atmosphere will be too high even for the refracting materials used).

The 'allowed' angle of re-entry is $-6.2° \pm 1°$ relative to the Earth's horizon.

3. Future space travel and exploration will entail a combination of new technologies based on current and emerging knowledge

§ Discuss the limitation of current maximum velocities being too slow for extended space travel to be viable

Scientists have not yet been able to produce speeds of spacecraft more than a few tens of thousands of kilometres per hour. When travelling to distant planetary objects, the engines of spacecraft are not on as spacecraft rely on inertia to move along. To increase the speed significantly would require the engines to be operating, which would require more fuel. More fuel would require more thrust putting the spacecraft into orbit, which would require more fuel and so on.

To increase the speed of spacecraft to values that would make interplanetary travel feasible requires a whole new technology (one not based on the emission of gases produced by combustion). Clearly, while current maximum velocities are just adequate for interplanetary travel, they are entirely inadequate for interstellar travel.

§ Describe difficulties associated with effective and reliable communications between satellites and earth caused by:

- distance
- van Allen radiation belts
- sunspot activity

Distance

Microwaves and radio waves, like all EM waves, travel through space at the speed of light. This is the fastest speed possible in our universe and therefore places a limit on the speed and response time of space communications. The immense distance involved in space communications creates a distance-related time lag. Also, as EM radiation obeys an *inverse square law*, there is a loss of signal strength as distance increases. This is referred to as *space loss*.

Van Allen radiation belts

There are two belts of energetic charged particles, mainly electrons and protons, lying at right angles to the equator of the Earth. Some of the solar wind particles become trapped in the Van Allen radiation belts. Intense solar activity can disrupt the Van Allen Belts. This in turn is associated with *auroras* and *magnetic storms*. The charged particles drifting around the Earth in the outer belt corresponds to an electric current and hence has an associated magnetic field. Once or twice a month this current increases and as a result its magnetic field increases. This can lead to interference of short wave radio communication, errors in communication satellites and even failure of electrical transmission lines.

Sunspot activity

Sunspots are associated with the solar wind (consisting of a stream of charged particles). The solar wind affects the Earth’s magnetic field and this in turn affects radio communication.

4. Current and emerging understanding about time and space has been dependent upon earlier models of the transmission of light

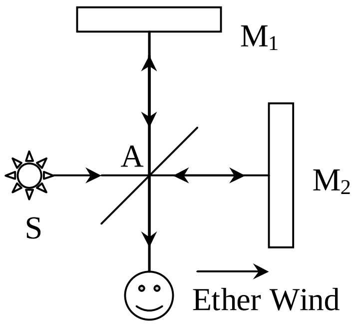
§ Outline the features of the ether model for the transmission of light

It was believed that light waves require a medium to propagate. Although nobody could find such a medium, belief in its existence was so strong that it was given a name – **the ether**.
The ether:

- Filled all of space, had low density and was perfectly transparent
- Permeated all matter and yet was completely permeable to material objects
- Had great elasticity to support and propagate the light waves

§ Describe and evaluate the Michelson-Morley attempt to measure the relative velocity of the Earth through the ether

The Ether Wind
Because the Earth was moving around the Sun, it was reasoned that an *ether wind* should be blowing past the Earth. However, if a wind blows, the speed of sound relative to the stationary observer would vary. Thus it was believed that the speed of light should vary due to the presence of the "ether wind". It was in an attempt to detect this difference that Michelson and Morley did their famous experiment.



The Michelson-Morley Experiment
Light sent from S is split into two perpendicular beams by the half-silvered mirror at A. These two beams are then reflected back by the mirrors M_1 and M_2 and are recombined in the observer's eye. An interference pattern results from these two beams.

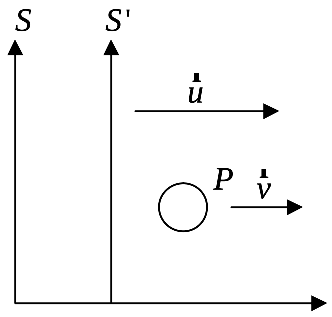
The beam AM_1 travelled across the ether, whilst AM_2 travelled with and against the ether. The times to do this can be shown to be different and so introduce a phase difference between the beams. When the entire apparatus was rotated through 90°, *a change in the interference pattern was expected*. None was observed.

The result of the **Michelson-Morley experiment** was that no motion of the Earth relative to the ether was detectable.

§ Discuss the role of critical experiments in science, such as Michelson-Morley's, in making determinations about competing theories

From a hypothesis, predictions are made of what should happen if a particular experiment is performed. If the results are not in agreement with the prediction, the hypothesis is incorrect. As we have seen, the fact that a null result was found from this experiment showed the ether hypothesis to be invalid. This opened up a completely revolutionary view of space and time with the work of Einstein.

§ Outline the nature of inertial frames of reference



Frames of Reference
Frames of reference are objects or coordinate systems with respect to which we take measurements.

Position
In maths, the Cartesian coordinate system is used and position is referred to the axes x, y and z. In experiments in class, the laboratory is the frame of reference.

Velocity
An object *P* travels with *velocity v* with respect to a reference frame *S*. Another frame *S'* moves with velocity *u* relative to *S*. The velocity of *P* relative to *S'* is $v' = v - u$. *Velocity thus depends upon the reference frame.*

Inertial Frames of Reference
An **inertial frame of reference** is one that is moving with constant velocity or is at rest (the two conditions being indistinguishable). In such reference frames, Newton's Law of Inertia holds.

A **non-inertial frame of reference** is one that is accelerating.

§ Discuss the principle of relativity

Three hundred years before Einstein, Galileo posed a simple idea, now called the **principle of relativity**, which states that all steady motion is relative and cannot be detected without reference to an outside point. This idea can be found built into Newton's First Law of Motion as well.

Two points to be reinforced:
- The principle of relativity applies only for non-accelerated steady motion
- This principle states that within an inertial frame of reference you cannot perform any mechanical experiment or observation that would reveal to you whether you were moving with uniform velocity or standing still.

- Identify the significance of Einstein's assumption of the constancy of the speed of light

In 1905, Albert Einstein proposed that **the speed of light is constant** and is independent of the speed of the source or the observer. This premise explained the 'negative' result of the Michelson-Morley experiment and showed that the *ether concept was not needed*.

As a consequence of this *'law of light'* it can be shown that there is no such thing as an absolute frame of reference. All inertial reference frames are equivalent. That is, *all motion is relative*. The laws of physics are the same in all frames of reference; that is, the principle of relativity always holds.

- Recognise that if c is constant then space and time become relative

In Newtonian physics, distance and velocity can be relative terms, but time is an absolute and fundamental quantity. Einstein radically altered the assumptions of Newtonian physics so that now the speed of light is absolute, and space and time are both relative quantities that depend upon the motion of the observer. *(Our reality is what we measure it to be. <u>Reality and observation cannot be separated</u>. Remember this as we proceed).*

- Discuss the concept that length standards are defined in terms of time with reference to the original meter

…In other words, the measured length of an object and the time taken by an event depend entirely upon the velocity of the observer. *(This is why our current standard of length is defined in terms of time – the **metre** is the distance travelled by light in a vacuum in the fraction 1/299792458 of a second).*

- Identify the usefulness of discussing space/time, rather than simple space

…Further to this, since neither space nor time is absolute, the theory of relativity has replaced them with the concept of a space-time continuum. *(Space and time, not just space, are relative quantities).*

- Account for the need, when considering space/time, to define events using four dimensions

…Any event then has four dimensions (three space coordinates plus a time coordinate) that fully define its position within its frame of reference.

§ Explain qualitatively and quantitatively the consequence of special relativity in relation to:

- The relativity of simultaneity
- The equivalence between mass and energy
- Length contraction
- Time dilation

The Relativity of Simultaneity (simultaneity and the velocity of light)
Observers in relative motion will disagree on the **simultaneity** of events separated in space.

The Equivalence Between Mass and Energy
The mass of a 'moving' object is greater than when it is 'stationary' – it experiences mass dilation (covered later).

Since c is the maximum speed in the universe it follows that a steady force applied to an object cannot continue to accelerate. It follows that the inertia, that is the resistance to acceleration, must increase. But inertia is a measure of mass and so the mass has increased.

It is this increase in mass that prevents any object from exceeding the speed of light, because as it accelerates to higher velocities its mass increases, which means that further accelerations will require even greater force. This is further complicated by time dilation because, as speeds increase to near light speed, any applied force has less and less time in which to act. The combined effect is that as mass becomes infinite and time dilates, an infinite force would be required to achieve any acceleration at all. *Sufficient force can never be supplied to accelerate beyond the speed of light.*

If force is applied to an object, then work is done on it – energy is given to the object. This energy would take the form of increased kinetic energy as the object speeds up. But at near light speed the object does not speed up. The applied force is giving energy to the object and the object does not acquire the kinetic energy we would expect. Instead, it acquires extra mass. Einstein made an inference here and stated that the mass (or inertia) of the object contained the extra energy.

Relativity results in a new definition of energy as follows:

$E = E_k + mc^2$ where E = total energy, E_k = kinetic energy, m = mass, c = speed of light

When an object is stationary, it has no kinetic energy, but still has some energy due to its mass. This is called its mass energy or **rest energy** and is given by:

$E = mc^2$ where E = rest energy (J), m = mass (kg), c = speed of light (3×10^8 m s^{-1})

Implications of Special Relativity:

To measure speed we need to measure distance and time. If *c* remains constant, then it follows that distance (length) and time must change. *Space and time are relative concepts.*

Length Contraction (the Lorentz-FitzGerald Contraction)
The length of a 'moving' rod appears to contract in the direction of motion relative to a 'stationary' observer.

$$l = l_0\sqrt{1-\frac{v^2}{c^2}}$$

where l is the moving length, l_0 is the 'rest' length (that is, the length as measured by an observer at rest with respect to the rod) and v is the speed of the rod.

Time Dilation
Time in a 'moving' frame appears to go slower relative to a 'stationary' observer

$$t = \frac{t_0}{\sqrt{1-\frac{v^2}{c^2}}}$$

where t is the observed time for a 'stationary' observer and t_0 is the time for an observer travelling in the frame. t_0 is called the **proper time** *(this is the time measured by an observer present at the same location as the events that indicate the start and end of an event).*

Mass Dilation
The mass of a 'moving' object is greater than when it is 'stationary'.

$$m = \frac{m_0}{\sqrt{1-\frac{v^2}{c^2}}}$$

where m is the mass for a 'moving' object and m_0 is the mass for that object when it is 'stationary.'

§ Discuss the implications of time dilation and length contraction for space travel

The relativity of time allows for space travel into the future but not into the past. When travelling at relativistic speeds (0.1*c* or faster), relativity influences the time that passes on the spacecraft. Astronauts on a relativistic interstellar journey would find their trip has taken fewer years than observed on Earth.

Core Topic Two: Motors and Generators

1. Motors use the effect of forces on current-carrying conductors in magnetic fields

§ Identify that moving charged particles in a magnetic field experience a force	*Charged* particles *moving* in an external magnetic field will experience a force. If the moving charged particles are flowing through, and confined within, a conductor that is in an external magnetic field, the conductor will also experience a force. This effect is known as the **motor effect**. F = qvB Use left hand "FBI gun" An example: **Van Allen Radiation Belts** The Earth's magnetic field captures charged particles from the solar wind (low energy) and cosmic rays (high energy). The charges are force to spiral along the field lines accumulating into two doughnut-shaped belts of "radiation" called the upper and lower Van Allen radiation belts.

§ Discuss the effect, on the magnitude of the force on a current-carrying conductor, of variations in:

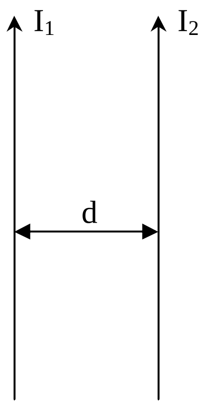
The strength of the magnetic field in which it is located	…The force is proportional to the magnetic field strength, ***B***
The magnitude of the current in the conductor	…The force is proportional to the current, ***I***
The length of the conductor in the external magnetic field	…The force is proportional to the length, ***L***
The angle between the direction of the external magnetic field and the direction of the length of the conductor	…The force is at a maximum when the conductor is at right angles to the field, and is zero when the conductor is parallel to the field. The magnitude of the force is proportional to the component of the field that is at right angles to the conductor.

$$F = BIl \sin q$$

§ Describe qualitatively and quantitatively the force on long parallel current-carrying conductors:

$$\frac{F}{l} = k\frac{I_1 I_2}{d}$$

(Ampere's law)



Ampere's Law
Two parallel wires, each carrying a current, will exert a force on the other. This happens because each current produces a magnetic field (as in Oersted's experiment). Therefore each wire finds itself carrying a current across the magnetic field produced by the other wire and hence experiences a force.

Determining the magnitude of the force between two parallel conductors
The magnetic field strength at a distance, *d*, from a long straight conductor carrying a current, *I*, can be found using the formula:

$$B = \frac{kI}{d}$$

where k = 2.0×10^{-7} N A^{-2}

The magnitude of the force *experienced* by a length, *l*, of a conductor due to to an external magnetic field is:

$$F = I_2 lB$$

or

$$F = I_2 l\left(\frac{kI_1}{d}\right)$$

rearranged

$$\frac{F}{l} = k\frac{I_1 I_2}{d}$$

If currents are in the **same** direction, then the conductors will **attract**.
If currents are in **opposite** directions, then the conductors will **repel**.

§ Define torque as the turning moment of a force using:

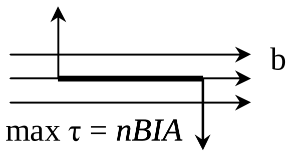
$$t = Fd$$

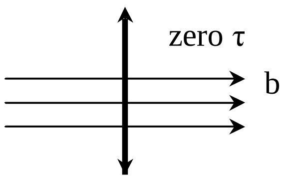
Torque is **turning force**. Its' units are Newton-metres (Nm).

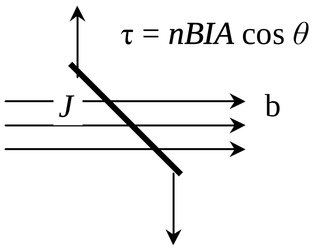
$$t = Fd$$

where τ = torque, in Nm
F = force, in N
D = distance from rotational axis, in m

§ Identify the forces experienced by a current-carrying loop in a magnetic field and describe the net result of the forces

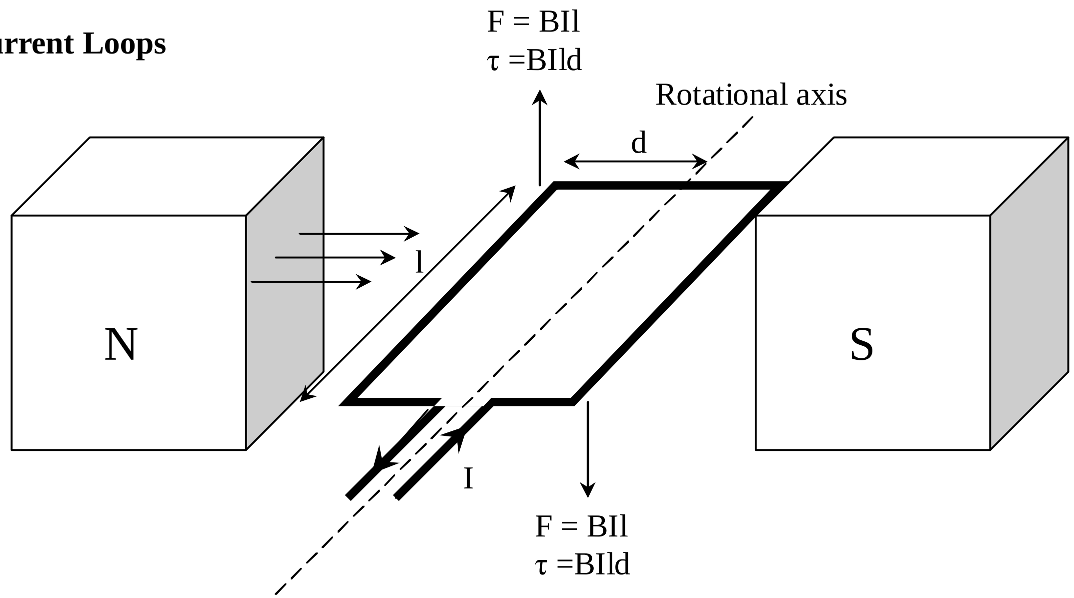






Generally, $\tau = nBIA \cos\theta$

Current Loops



$$\begin{aligned} t &= t_1 + t_2 \\ &= BIld + BIld \\ &= 2BIld \\ &= BI(l \times 2d) \\ &= BIA \end{aligned}$$

(For each turn of the loop)

§ Account for the motor effect due to the force acting on a current-carrying conductor in a magnetic field

The motor effect
Recall that charged particles moving in an external magnetic field will experience a force. If the moving charged particles are flowing through, and confined within, a conductor that is in an external magnetic field, the conductor will also experience a force.

An electric motor is a device that transforms electrical potential energy into rotational kinetic energy.

§ Describe the main features of a DC electric motor

§ Discuss the importance of the invention of the commutator for developing electric motors

§ Describe the role of the metal split ring and the brushes in the operation of the commutator

Anatomy of a DC motor

- **Permanent magnets:** provide an external magnetic field in which the coil rotates. As the magnets are fixed, they are known as the **stator**.
- **Rotating coil:** carries a direct current that interacts with the magnetic field, producing torque.
- **Armature:** is made of ferromagnetic material and allows the coil to rotate freely on an axle. The armature and coil together are known as the **rotor**. The armature protrudes from the motor casing, enabling the movement of the coil to be used to do work.
- **Commutators:** reverse the current of the coil every half turn to maintain consistent direction and torque. It is a mechanical switch that automatically changes the direction of the current flowing through the coil when the torque falls to zero.
- **Brushes:** maintain electrical contact of coils with the rest of the circuit.

The development of DC motors outstripped that of AC motors and generators for two reasons:
- Voltaic batteries could supply power
- They could use powerful electromagnets that were far stronger than permanent magnets

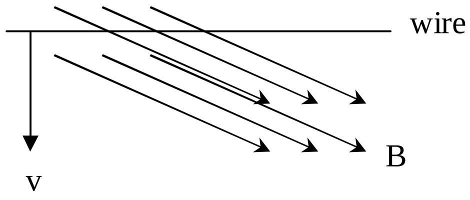
The development of the commutator was important because it led to the development of modern electric motors and generators. It enabled motors to provide steady circular motion of a drive shaft.

§ Describe how the required magnetic fields can be produced either by current-carrying coils or permanent magnets

The magnetic field of a DC motor can be provided either by permanent magnets or by electromagnets.

2. The relative motion between a conductor and magnetic field is used to generate an electrical voltage

§ Outline Michael Faraday's discovery of the generation of an electric current by a moving magnet



Faraday had found that 3 things are necessary to generate (or "induce") an EMF (voltage supply):

- **A magnetic field** (from some magnets or electromagnet)
- **A conductor** (eg. wire or coil of wire)
- **Relative motion** / change between the field and the conductor

If the conductor formed a closed loop then an induced current would also flow.

If this wire is dropped so that it cuts flux lines, then a voltage appears between the ends because electrons are forced to the right. They eventually stop moving because they create an electric field pushing them back.

As long as the magnet is moving, an emf and current is induced.

Faraday's Law

$$e = -\frac{n\Delta\Phi}{t}$$

where $e =$ induced EMF, in V

$n =$ number of turns on coil

$\Delta =$ change in

$\Phi =$ magnetic flux, in Wb

$= \mathrm{BA}$

$\mathrm{B} =$ magnetic flux density (field strength), in T

$\mathrm{A} =$ area of coil in m^2

$t =$ time taken for $\Delta\Phi$ to occur

The induced voltage can be increased by:

Increasing n: more turns on the coil
Increasing B: use strong magnets
Increasing A: use a bigger coil
Decreasing t: go faster!

§ Define magnetic field strength B as magnetic flux density

Magnetic flux density is the magnetic flux per unit area and is a measure of the magnetic field strength.

§ Explain the concept of magnetic flux in terms of magnetic flux density and surface area

$$\Phi = BA\sin q$$

where $B =$ magnetic flux density, in T

$A =$ area, in m^2

$\Phi =$ magnetic flux, in Wb

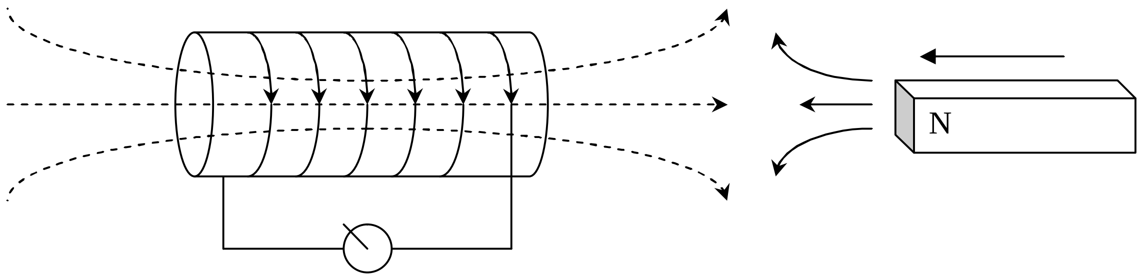
§ Explain generated potential difference as the rate of change of magnetic flux through a circuit

The induced emf is proportional to the rate of change of flux through the circuit. See Faraday's Law (above).

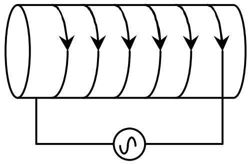
§ Account for Lenz's Law in terms of conservation of energy and relate it to the production of back emf in motors

Lenz's Law

This is a supplementary law to Faraday's Law. It says that any induced emf or current will have a direction that opposes the change that caused it. This is really just a restatement of the law of conservation of energy because the induced electrical energy has come from the thing that causes the original motion. Eg. In a hydroelectric power station, the kinetic energy of flowing water is converted into electrical energy.



§ Explain that, in electric motors, back emf opposes the supply emf



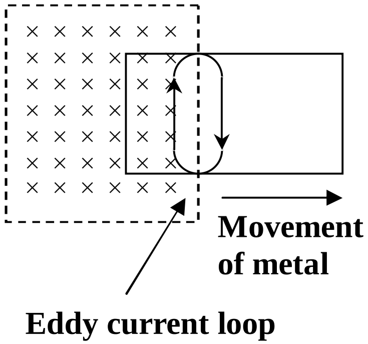
The coil becomes an electromagnet and generates an alternating B field BUT it also experiences the changing B field and generates its own emf that opposes the applied emf.

Back emf
Back emf is generated in any coil that experiences changing B fields, even though it is producing them.

Note that back emf is frequency dependent – the higher the frequency of the changing field, the greater the back emf produced.

Back emf is also produced in the rotating coil of a motor:
- When the motor is spinning at its operating speed, back emf will have its max value, but…
- When the motor is just turned on it isn't spinning yet so there is no back emf.
- This can lead to excessive current so the motor may be protected by using a "starting resistance" that limits current. When up to speed the resistor is taken out of the circuit.

§ Apply Lenz's Law to the production of eddy currents



Eddy Currents - are induced currents (usually unwanted or unintended) in two-dimensional conductors (eg. sheet metal) or three-dimensional conductors (eg. a block of steel). Sometimes it is necessary to design against them. Eg. the core of a motor is made of soft iron, and is made of thin layers (laminated) to prevent eddy currents.

Some devices rely on eddy currents to work:
<u>Electromagnetic braking</u> – a moving conductor near magnets will slow down because the eddy currents oppose its motion.
<u>Electromagnetic switching</u> – security 'gates' that are really coils with AC generate a high frequency B field. Metal in this field develops eddy currents that work against the field, slowing it down. A detector circuit picks up on this and sets off an alarm.
<u>Induction Cooktops</u>- are an application of Faraday's Law. Instead of a heating element, this cooktop contains a set of coils with alternating current passing through them. This produces a changing B field above the cooktop. A metal saucepan placed on the cooktop is a conductor in the changing B field and therefore an electric current is induced in the base of the pan. The current heats the pan, and this heat cooks the food. Induction cooktops are approximately twice as efficient as a gas cooktop, but are expensive to purchase.

3. Generators are used to provide large scale power production in isolated areas and as a backup in emergency situations

§ Identify the main components of a generator

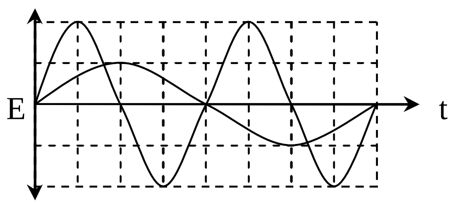
An **electric generator** (dynamo) is a device that includes all of the elements necessary to transform mechanical kinetic energy to electricity according to Faraday's Law:

- A magnetic field (provided by a set of permanent magnets);
- A conductor (a coil mounted on an axle, so it can spin);
- Relative motion (the coil is made to spin by some other form of energy).

§ Compare the structure and function of a generator to an electric motor

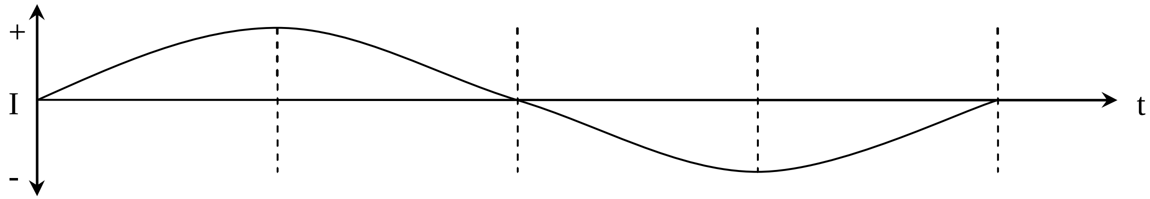
In fact, most generators are constructed just like a motor, however the flow of energy through them is different.
Motor: electrical energy à kinetic energy
Generator: kinetic energy à electrical energy

§ Describe the operation of an AC and a DC generator

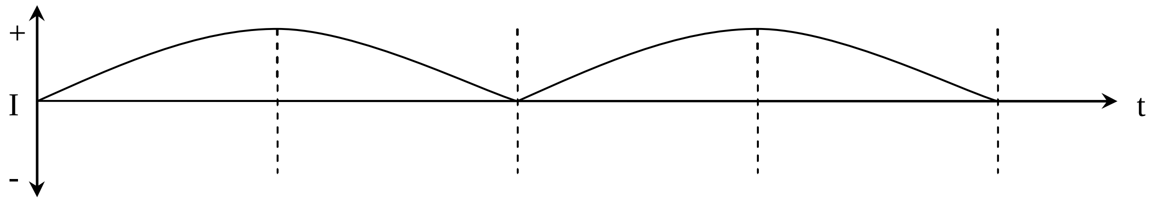


Doubling the frequency of rotation doubles the maximum induced emf

EMF is generated in the coil and a circuit is completed to the outside world through ring connectors, just like motors. If standard slip rings are used then a dynamo naturally produces alternating current AC.



If a split ring commutator is used instead, then the direction of the current flowing from the coil is reversed every ½ cycle. This produces a pulsing type of direct current DC.



§ Discuss the energy losses that occur as energy is fed through transmission lines from the generator to the consumer

Even good electrical conductors like copper used to supply electricity, sometimes through considerable cable lengths to towns and cities, generate substantial resistances. It follows that to minimise energy loss in the wires, the current needs to be kept low (heating losses vary as the square of the current). This is achieved by transmitting the energy at high voltages.

§ Analyse the effects of the development of AC and DC generators on society and the environment

	Positive	Negative
Impact on society	- Improved lifestyle - Street lighting - Electric trains - Communication - Computerisation of many systems eg. banking, stock market - Industrial development → more jobs	- Possible risk of cancer living near distribution cables - Longer working hours - Reliance on electricity leaves us vulnerable to systems loss due to electrical failure
Impact on environment	- Lots of electric trains have reduced pollution from steam trains and made public transport more available - Electricity has replaced older, more-polluting technologies eg. electrical heating instead of coal burning in fireplaces	- Burning coal in power stations produces smoke and CO_2 (a greenhouse gas) - Nuclear power stations produce radioactive water & have a risk of nuclear accident - Hydroelectric schemes redirect water away from river habitats - Mining impacts negatively on environment - Visual pollution of cables

§ Assess evidence about the physiological effects on humans living near high voltage power lines

1979 study found children living near high voltage power lines appeared to develop a particular form of cancer. 1997 study showed no evidence of an increase risk of childhood cancer at residential magnetic field levels. 1998 panel stated that EM fields should be considered "possible human carcinogens" and that there is "no conclusive and consistent evidence that EM fields cause any human disease."

4. Transformers allow generated voltage to be either increased or decreased before it is used

§ Explain the purpose and principles of transformers in electrical circuits

A **transformer** is a device that alters the voltage and current of an electricity supply.
The AC voltage source produces an alternating current in the primary coil. This produces an alternating B field that threads through the secondary coil. The secondary coil now has:

- Conductor
- B field
- Change

and therefore generates its own voltage. If there is a closed loop then an alternating current will flow as well.

§ Compare step-up and step-down transformers

Step-up transformers: increase voltage and decrease current
Step-down transformers: decrease voltage and increase current

§ Determine the relationship between the ratio of the number of turns in the primary and secondary coils and the ratio of primary to secondary voltage

V_p = primary voltage (voltage in)
I_p = primary current
n_p = number of turns on primary coil
V_s = secondary voltage (voltage out)
I_s = secondary current
n_s = number of turns on secondary coil

$$\frac{V_p}{V_s} = \frac{n_p}{n_s}$$

If 100% efficient (this needs perfect "flux linkage", usually using an iron core) then:
Power in primary = Power in secondary

$$\therefore V_p I_p = V_s I_s$$

$$\therefore \frac{V_p}{V_s} = \frac{I_s}{I_p}$$

$$\therefore \frac{V_p}{V_s} = \frac{n_p}{n_s} = \frac{I_s}{I_p}$$

§ Explain why voltage transformations are related to the conservation of energy	The *Principle of Conservation of Energy* states that energy cannot be created or destroyed but that it can be transformed from one form to another. This means that if a step-up transformer gives a greater voltage at the output, its current must be decreased: i.e. power in = power out.
§ Explain the role of transformers in electricity sub-stations	NSW power stations produce electricity with a voltage of about 23,000 V and a current of about 30,000 A. Unfortunately, this amount is too high to be sent through a cable. This is because it heats the cable causing energy loss. This is called joule heating and happens because: $P = I^2R$ So to reduce joule heating, the current must be reduced as much as possible with a step-up transformer. Additional transformers between the power station and consumer (in sub-stations) gradually step-down the voltage, to 240 V by the time it gets to household users. This is because at high voltages, electricity can conduct through air, making it dangerous for use in the home.
§ Discuss why some electrical appliances in the home that are connected to the mains domestic power supply use a transformer	Most electronic circuits are designed to operate at low DC voltages of between 3 V and 12 V. Therefore, household appliances that have electronic circuits in them will have either a plug-in transformer or an inbuilt transformer to step down the domestic 240 V supply. These transformers also have a rectifier circuit built into them that converts AC to DC. TVs also contain a step-up transformer for producing the high voltages needed for the CRT.
§ Analyse the impact of the development of transformers on society	The development of the generator and transformer has allowed for the setting up of national power grids in almost every country, making that most convenient and flexible form of energy, electricity, accessible from many miles away. The transformer's role is to step voltage up and down to make efficient transportation and distribution possible.

5. Motors are used in industries and the home usually to convert electrical energy into more useful forms of energy

§ Describe the main features of an AC electric motor

AC induction motor:
- The *rotor – end rings* short circuit *non-ferrous rotor bars*, that is sealed i.e. no external connections at all (usually a "squirrel cage"). Encased in a *laminated iron armature*.
- The *stator* – surrounding electromagnet.
- Connection to stator – the surrounding electromagnet receives the AC.

AC (synchronous) motor:
- A rotating coil
- Surrounding magnets
- Connection to coil via <u>slip rings</u> (commutator for DC motor)

In an **AC induction motor**, the principle of operation is:
1. AC to surrounding electromagnet, which…
2. Produces an oscillating (rotating) B field, which…
3. Induces a current in the rotor, which…
4. Turns the rotor into an electromagnet that…
5. Tries to oppose the field being generated by the stator.
6. The stator and the rotor push against each other (using their B fields), which…
7. Causes the rotor to turn! Brilliant!

§ Explain that AC motors usually produce low power and relate this to their use in power tools

Power is the rate of work. Work is done when energy is transformed from one type to another. Induction motors are considered to produce low power because the amount of mechanical work they achieve is low compared with the electrical energy consumed. The 'lost power' of induction motors is consumed in magnetising the working parts of the motor and in creating induction currents in the rotor. AC induction motors are considered to be unsuitable for use in heavy industry because their low power rating would make them too expensive to run when performing a specific task. However, they are used extensively in power tools and electric domestic appliances where the loss of power is not economically significant.

§ Explain the advantages of induction motors

Advantages of AC induction motors:
1. Simplicity of design;
2. High efficiency (hence low maintenance – there are no brushes or commutators to wear out);
3. Relatively low cost

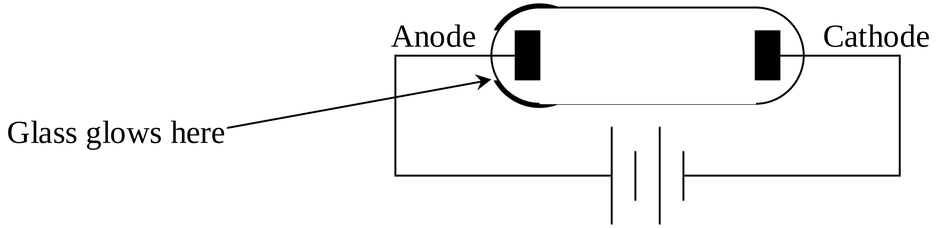
Core Topic Three: From Ideas to Implementation

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

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

Discharge Tubes

- Investigation of vacuum tubes could not occur until good vacuum pumps had been invented. A vacuum tube is a glass tube fitted with an electrode at either end, and almost all of the air sucked out.
- The positive electrode is the "anode"; The negative electrode is the "cathode". When a ***high voltage*** is connected between the electrodes, an invisible ray travels from the cathode to the anode. They were called "cathode rays". Cathode rays cause glass to glow green.
- A discharge tube is a cathode ray tube with a vacuum pump fitted, so that the air pressure inside the tube can be varied. At different air pressures, different bright effects appear in the tubes e.g. bands, striations and dark spaces. These are caused by cathode rays striking atoms in the air inside the tube. The atoms become excited then release photons of visible light
- A beam of electrons travels from the cathode to the anode and can be deflected by electrical and/or magnetic fields.



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

In 1892 Hertz demonstrated that cathode rays could penetrate thin metal foils. This he believed supported a wave nature.
In 1895 Jean-Baptise Perrin showed that cathode rays deposited negative charges on impact with an object, suggesting a particle nature.
There was controversy over the nature of cathode rays – waves or particles.

§ Identify that charged plates produce an electric field

If metal plates are separated by a distance and are attached to a power source, an electric field will be produced between them. E = V/d

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

Recall that the force (F) acting on a charge (q) <u>moving with a velocity (v)</u> at an angle to a magnetic field (B), is given by:

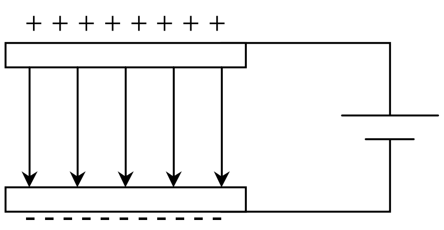
$$F_B = qvB$$

Where F_B = magnetic force (N)
q = charge (C)
v = velocity of charge (ms^{-1})
B = magnetic field strength (T)

§ Discuss qualitatively the electric field strength due to a point charge, positive and negative charges and oppositely charged parallel plates.

If a positive charge is placed near another positive charge, it will experience a force of repulsion.
A positive charge placed in a field will experience a force in the direction of the arrow.
A negative charge placed in a field will experience a force opposite to the direction of the arrow.

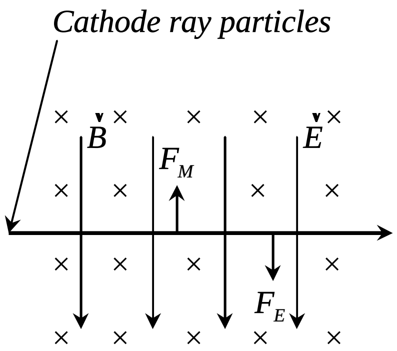
§ Describe quantitatively the electric field due to oppositely charged parallel plates



$$F_E = qE$$

Where F_E = electric force (N)
q = charge (C)
E = electric field strength (NC^{-1})

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



$$\therefore F_M = F_E$$
$$qvB = qE$$
$$\therefore v = \frac{E}{B}$$

Thomson adjusted the strength of the fields so that the particles were <u>not</u> deflected.

By carefully measuring the strength of the fields, Thomson could calculate v.

J. J. Thomson's Experiment

- By fitting plates to his CRT, he could subject the cathode rays to an electric field. The rays deflected, proving that they were **charged particles, not electromagnetic waves.**
- He noticed that the rays deflected toward the positive plate, proving that they were **negatively charged particles**.
- By crossing electric and magnetic fields, Thomson was able to deduce the **velocity of the cathode rays**.

- By turning off the E field, the particles followed a circular arc caused by the B field. The magnetic force was acting like a **centripetal force**.

$$qvB = \frac{mv^2}{r}$$
$$\therefore \frac{q}{m} = \frac{v}{Br}$$

- Thomson had already measured B and worked out v. By measuring the radius of curvature r, he could then calculate q/m, i.e. **the charge/mass ratio of an electron.**
- q/m for these particles was 1800 times greater than for a hydrogen ion, the simplest known atomic ion.
- Thomson quickly compared the charges and found them to be about the same (though opposite in sign)
- Therefore mass for cathode ray particles was **1800 times smaller** than hydrogen
- Therefore cathode ray particles were subatomic particles!

    - This was the first discovery of subatomic particles
    - They were later called **electrons.**

§ Outline the role in a cathode ray tube of:

Electrodes in the electrode gun

The electric field

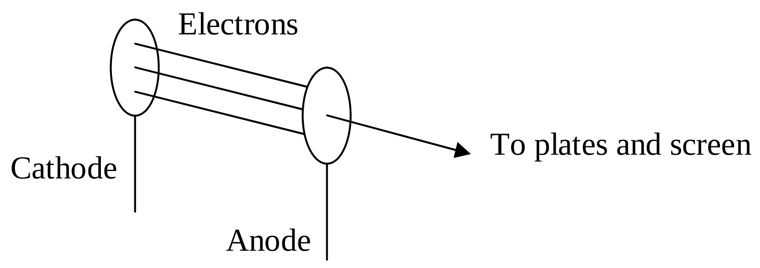
The fluorescent screen

The Cathode Ray Tube
Each CRT has a vacuum tube/chamber, a cathode, an anode, and a target.

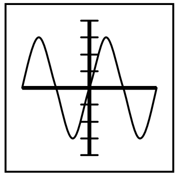
Electrodes in the electron gun
The electron gun produces a narrow beam of electrons. It consists of a *filament*, a *cathode* and two open-cylinder *anodes*. The anodes help to accelerate and focus the electrons.
A ring shaped electrode – the *grid* – between the cathode and anodes controls the brightness of the spot by controlling the number of electrons emitted by the gun. By making the grid negative with respect to the cathode the number of electrons, and hence the brightness is reduced.

The electric field
Acts as a *deflection* system. It consists of two sets of parallel plates connected to a parallel plates connected to a potential difference. This produces an *electric field* between the plates. The Y-plates control the vertical deflection and the X-plates the horizontal deflection.

The fluorescent screen
The inside glass of the end of the tube is coated with a fluorescent material for example, zinc sulphide. When an electron beam hits the screen, the coating fluoresces and a spot of light is seen on the screen. The screen acts as a *detector* of cathode rays.

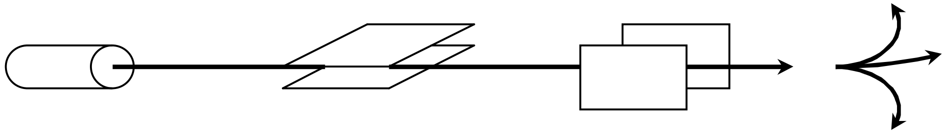


§ Outline applications of cathode rays in oscilloscopes, electron microscopes and television sets



The Cathode Ray Oscilloscope (CRO)
Is an electronics diagnostics device because it can show a graph of how voltages vary over time.

Deflection of the electron beam is achieved by two sets of plates.
Horizontal plates cause vertical deflection while vertical plates cause horizontal deflection.



TV Tube
An electron gun again produces the electron beam. Coils are used instead of plates, however. Electric current through the coils produce magnetic fields that can deflect the beams quickly from side to side, and more slowly from bottom to top. In this way the beam scans the entire screen. By varying the intensity of the beam, a picture is built up. The picture is refreshed 50 times / second, which is too fast to be noticed by the human eye.

The Electron Microscope
Uses electrons instead of light. Their wavelength is 100,000 times smaller than visible light, therefore their resolving power is 100,000 times greater.
- A “sample” is placed inside the chamber (which is really the CRT)
- The air is then sucked out
- An electron gun produces the electron beam
- Coils produce magnetic fields to focus the beam (“magnetic lenses”)
- The beam scans over the surface of the sample
- Detectors pick up the reflected and scattered electron beam, and from this information a 3 dimensional image is constructed

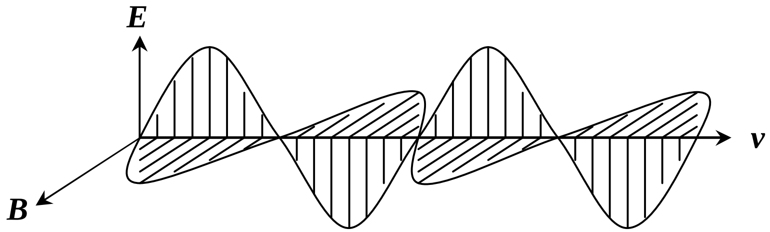
§ Discuss the impact of increased understandings of cathode rays and the development of the oscilloscope on experimental physics

The introduction of **electronic control systems** into all forms of science and industry has seen the cathode ray oscilloscope (CRO) become one of the most widely utilised test instruments. Because of its ability to make ‘voltages’ visible, the cathode ray oscilloscope is a powerful diagnostic and development tool.

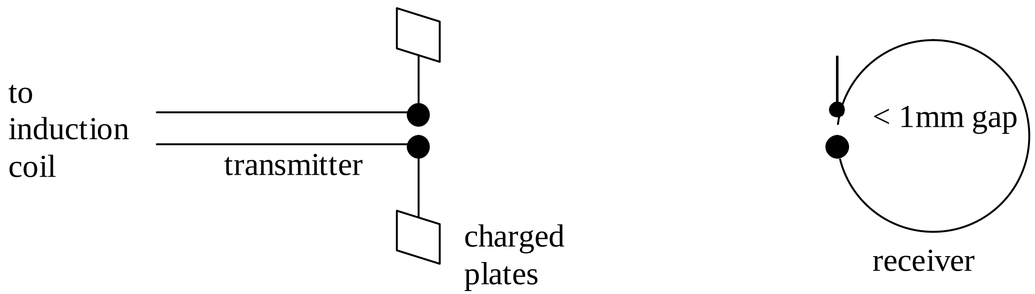
2. The reconceptualisation of the model of light led to an understanding of the photoelectric effect and black body radiation

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

Recall: **Maxwell's theory of electromagnetic waves**
In 1864 Maxwell, through a set of four brilliant equations, predicted a range of invisible waves made up of an electric and magnetic wave that regenerate each other. The speed of these waves was calculated to be 3×10^8 ms^{-1} and probably included light.

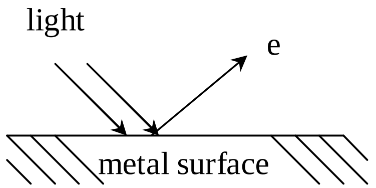


Heinrich Hertz's Experiment: (proving Maxwell's theory)
Performed in 1886, Hertz built equipment to generate and transmit EM waves with $\lambda \approx 1$m. He also had a separate receiver (a loop of wire) located about 20m away. Spark gaps were included to show when high voltage AC was present in the transmitter or receiver. The receiver spark only appeared when the transmitter spark was present. Hertz hypothesised that the sparks set up *changing electric and magnetic fields that propagated as an electromagnetic wave*, as postulated by Maxwell. He showed that these were waves being transmitted because he could *reflect, refract and polarise* them. By measuring the frequency, he calculated v ($v = f\lambda$) and it came out as 3×10^8 ms^{-1}. These properties proved Maxwell's theory and as they are also exhibited by light, Hertz was able to provide experimental evidence that *light is a form of transverse electromagnetic wave*.



§ Describe Hertz's observation of the effect of a radio wave on a receiver and the photoelectric effect he produced but failed to investigate	Hertz observed that the transmitter spark was producing something else to assist the production of the receiver spark. Thinking it to be light, he performed a dispersion experiment and discovered that UV light from the transmitter spark was causing extra electrons to join the receiver spark, making it stronger. He did not investigate this further, but did report his observations.
§ Outline applications of the production of electromagnetic waves by oscillating electric charges in radio antennae	**Electromagnetic waves** are produced by *accelerating charges* such as electrons oscillating in a wire. Consider a charge oscillating with simple harmonic motion. The field lines 'produce' a sine curve where the amplitude of the wave represents the electric field intensity at that point. This changing E produces a changing B; the result is an electromagnetic wave. Simple radio aerials use an alternating electric current in the antenna, which continually accelerates electrons back and forth, hence producing electromagnetic radiation that has the same frequency as the alternating current operating in the antenna.

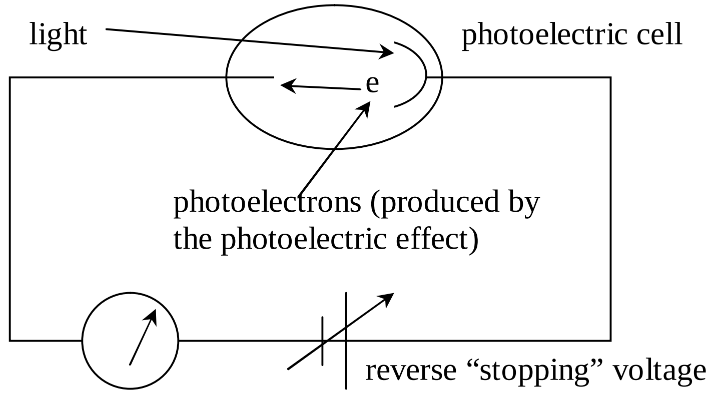
The Photoelectric Effect



***The Photoelectric Effect** is the emission of electrons from substances, in particular metals, when they are bombarded with light (usually in the high frequency range, such as ultraviolet). As previously mentioned, Hertz first discovered the photoelectric effect but failed to investigate this phenomenon any further.*

Philipp Lenard's Experiment

Lenard added a reverse voltage ("stopping voltage", V_{stop}) to measure the energy of the electrons. Cathode ray tubes became specialised for this investigation and gained some new names.



Lenard wanted to investigate the relationship between the energy of the photoelectron and the intensity of the light. His results were surprising!

He used a reverse current to stop the photoelectron's motion. This "stopping" voltage was a measure of their kinetic energy E_k.

$$qV_{stop} = \frac{1}{2}mv^2 = E_{k_{max}}$$

He used a carbon arc lamp that could be turned up or down to vary the light intensity.

He went further and placed colour filters in front of the lamp to investigate how the frequency of light affected the photoelectrons.

Classical physics could explain why the photoelectrons were produced – the incident light gave energy to the surface electrons until they had enough energy to escape the surface. Further, classical physics predicted that:

As light intensity increased, the energy of the photoelectrons would increase.

The frequency of the light should have no effect on the energy of the photoelectrons.

Lenard's Results:

1. Increasing the light intensity <u>did not</u> increase the energy of the photoelectrons, although it did produce more photoelectrons.
2. Increasing the frequency of the light (making it bluer) <u>did</u> increase the E_k of the photoelectrons.
3. There is a threshold frequency f_0 (which depends on the metal used) below which no photoelectric effect occurs, no matter how intense the light.
4. Above f_0, the photoelectric effect occurs no matter how dim the light.

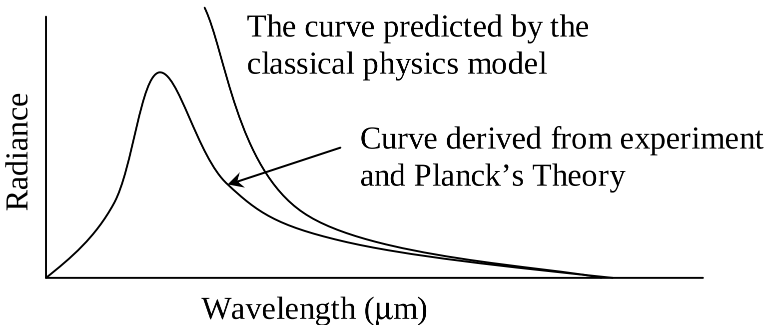
Classical physics could not explain these results!

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

Max Planck and Black Body Radiation – The Quantum Theory

A "black body" is a theoretical concept – an object that perfectly absorbs all radiation falling on it until it is warmer than its surroundings, and then becomes a perfect emitter. The radiation it emits is spread across the EM spectrum and has a peak that depends on the nature of the black body.

Black Body Radiation Curve:



Classical physics could not explain the shape of the black body radiation curve. Max Planck provided a complex explanation that did work but had to assume that the energy radiated in lumps he called "quanta". The energy of each quantum was given by: $E = hf$

Where E = energy of quantum, in J
f = frequency of radiation, in Hz
h = Planck's constant = 6.63×10^{-34} Js

§ Identify Einstein's contribution to the quanta and its relation to black body radiation

$$E_{k_{\max}} = hf - j = qV_{stop}$$

$$j = hf_0$$

$$E_{k_{\max}} = hf - hf_0$$

Einstein's Explanation of the Photoelectric Effect

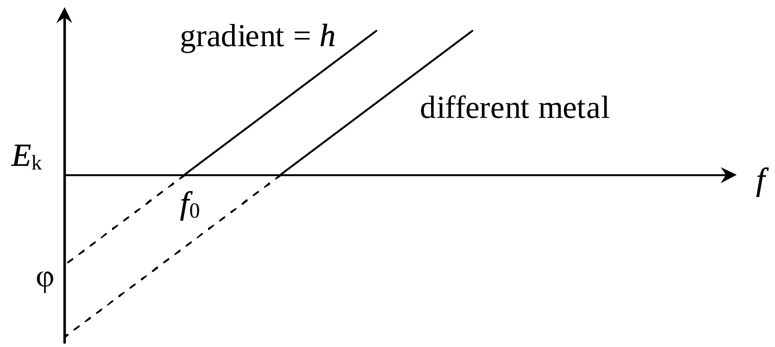
Einstein used Planck's idea and said that the incident light was quantised. He named a quantum of light a "photon". The energy of a photon depended on its frequency, according to $E = hf$.
Further, Einstein stated that a certain amount of energy was required by an electron to escape the metal surface. He called this the work function, φ (where $\varphi = hf_0$).

When a photon of light strikes an electron in the metal, it gives all of its energy to the electron.

If $E < \varphi$ then the electron cannot escape.
∴ no photoelectric effect, no matter how intense the light

If $E = \varphi$ then the electron can just escape, the photoelectric effect begins. This E corresponds to the threshold frequency f_0.

If $E > \varphi$ then the electron escapes with E_k left over:
$E_k = hf - \varphi$ (y = mx + b)



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

Light exists as photons, each with an energy represented as $E = hf$.
Light *intensity* depends on the *number* of photons.
Photons with the highest *energy* correspond to light of the highest *frequency*.

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

$$E = hf$$

and

$$c = f\lambda$$

The *energy of a light photon* of any known wavelength of light can be determined as they all travel with the same velocity (speed of light).

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

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

§ Describe the de Broglie model of electrons in orbits around atoms

Bohr's Model of the Atom

- Positive nucleus
- Electrons orbit nucleus in certain allowable orbits, each orbit represents a certain energy level with outer orbits having higher energies
- Electrons can jump up or down by absorbing or releasing an appropriate amount of energy (quanta)

However, Bohr did not know why these certain orbits were stable because his model suggests a natural instability.

De Broglie's Explanation

- Electrons move in waves with calculated wavelength $l = \frac{h}{mv}$
- He proposed that the circumference of each allowable orbit must be a *whole number of electron wavelengths*
- The allowable orbits then became *standing-wave patterns* of vibration ($\therefore$ stable) due to constructive interference
- Other orbits break down due to destructive interference

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

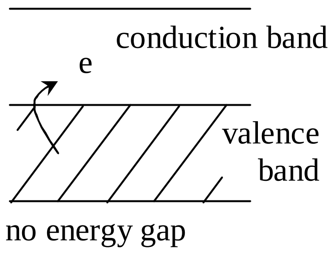
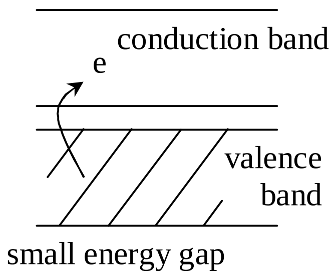
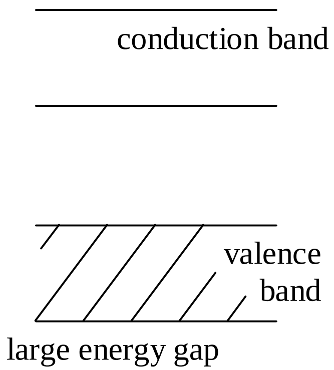
In a solid the atoms are linked together into a network or lattice by bonds. The bonds are either covalent (electron-sharing) or ionic (electron-swapping). As the outer electrons are used in this way they become common property to the lattice. Similarly, the energy levels or bonds which they occupy become common property of the lattice. That is, the outer energy levels are restricted to the atoms but extend across the lattice.

- The outermost energy level normally occupied by electrons is called the **valence band**
- The next band up (normally not occupied) is called the **conduction band**
- In order to conduct electricity, an electron must gain sufficient energy to jump up to the conduction band. This means the electron is no longer restricted to its atom and is free

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

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

Comparing Conductors, Semiconductors and Insulators

	Conductor	**Semiconductor**	**Insulator**
			
Charge carrier	Electron (-ve) in conduction band	Electron (-ve) in conduction band & electron hole (+ve) in valence band	None
Resistance	Low	Variable	High
Approx. # "free" electrons	1 per atom	1 per million atoms	none

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

The Creation of Charge Carriers in Semiconductors

Intrinsic Semiconductors

Within the crystal lattice of semiconductor, atoms are (usually) bonded to 4 other atoms, using covalent bonds. Here and there will be imperfectly formed bonds – “electron holes”. Electrons in the bonds require only a small amount of energy to jump out of the bond, travel a short distance and then jump into one of the available holes. In doing so it has left behind another hole.

As the electrons jump in one general direction, the holes appear to move in an opposite direction, as if they were positive charge carriers.

Hence, the provision of a small amount of energy to a semiconductor creates two types of charge carriers: *negatively charged electrons* and *positively charged electron holes*.

Normally there are as many electrons as holes, and this is referred to as an intrinsic semiconductor.

§ Describe how ‘doping’ a semiconductor can change its electrical properties

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

Extrinsic Semiconductors

Melting down a semiconductor then adding a small amount of impurity before recrystallising can alter the conducting properties of the semiconductor. This process is called “*doping*” and the material it forms is an “*extrinsic semiconductor*”.

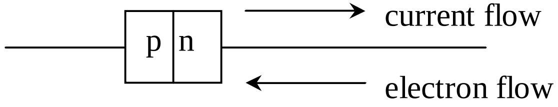
a) n-type semiconductors:
   If the impurity is from group 5 of the periodic table (eg Arsenic As, Phosphorous P) then it will have 5 outer electrons. Four will be used in covalent bonds, leaving one extra electron. Only one atom of impurity per 200,000 atoms of semiconductor is added. This material will have more negative charge carriers (electrons) than positives (holes).
b) p-type semiconductors:
   If the impurity is from group 3 (eg Boron B, Gallium Ge) then it will only have 3 outer electrons and can only form 3 covalent bonds. This will leave one empty spot (a hole) where there would otherwise have been an electron. This material will have more positive charge carriers (holes) than negatives (electrons).

Applications of Semiconductors

There are many ways that semi-conductors can be used to produce useful electronic devices. These are just a few:

Photovoltaic cells: a layer of n-type over a layer of p-type. Light shines on the n-type layer. This energy causes more conducting electrons to become available in the n-type, which produces a voltage between the layers. This allows it to be used like a battery.

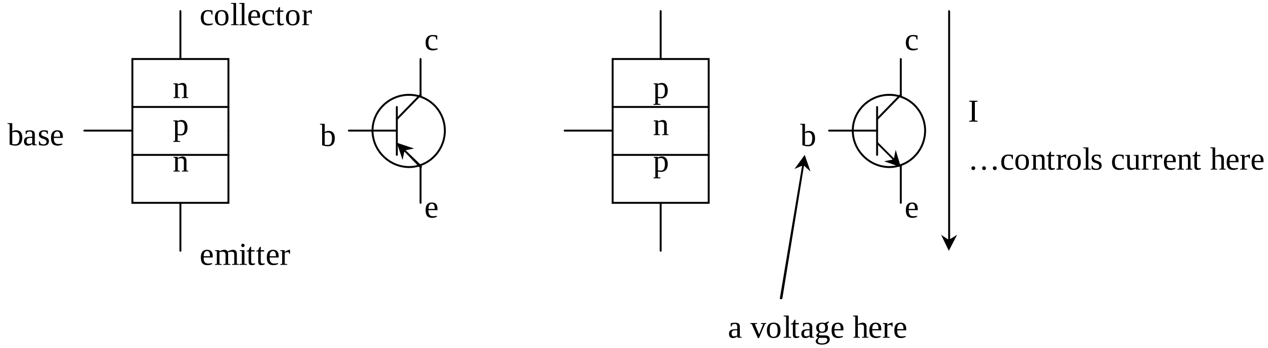
Diodes: a p-n junction



Current can only go one way through this device, so it acts like a one-way valve.

Diodes have become important circuit components to control the flow of electric current.

Transistors: a p-n-p or n-p-n sandwich



A transistor is like an electronic tap – a small voltage placed on the “base” can control a large current through the collector to the emitter.

Integrated Circuits: are thousands or millions of transistors (in circuits!) etched onto a single silicon chip. These have grown and developed into computer chips eg. Pentium 4 etc.

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

Germanium Vs Silicon
Transistors were invented in 1947, announced in 1948 and in production by 1950. These early transistors were made of germanium, as it was the *only semiconductor available in pure form* germanium was used in war-time military radio, so much research had already gone into how to grow it in pure form). However germanium has only *a small energy gap between its valence and conduction bands*. This made germanium transistors unreliable as the heat of normal operating conditions caused more conduction electrons to be created than expected. This made them behave erratically.

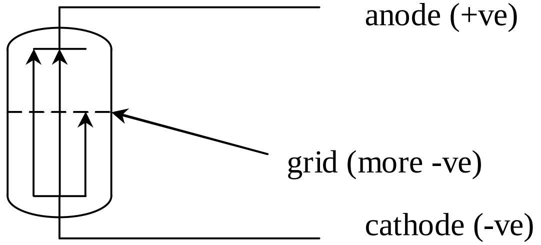
§ Explain why silicon became the preferred raw material for transistors

Silicon's *energy gap is slightly greater*, so once it was learned how to grow pure silicon, it was immediately used to make transistors (this was done in the early 1950's by Texas Instruments). Silicon transistors proved much more *reliable*.

Silicon is also more *abundant* than germanium, being very common in the Earth's crust.

§ Discuss differences between solid state and thermionic devices and discuss why solid state devices replaced thermionic devices

Transistors Vs Thermionic Valves
Thermionic valves were used during the first half of the twentieth century as an electronic switch or amplifier. They were essentially a small cathode ray tube with an extra controlling electrode, called a "*grid*". The problem was that these valves were *power hungry*, and often *unreliable*.

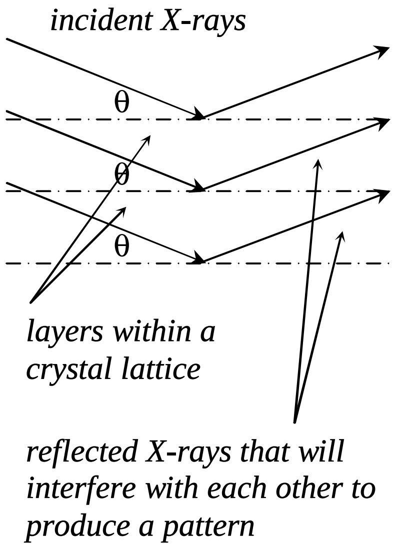


By controlling the voltage on the grid, more or less electrons could be allowed through to the anode.

Bell Labs (part of AT&T) developed the semiconductor replacement – the transistor. Transistors required much *less power* to run and were (eventually) *cheaper to produce*. They were also much *smaller*. Within a few years they had replaced valves almost completely.

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

- Outline the methods used by the Braggs to determine crystal structure and assess the impact of their contribution to an understanding of crystal structure



Recall:
Superposition – if two waves act in the same place at the same time they add up to give a combined effect.
Interference – the superposition of waves.
Interference pattern – interference in two or three dimensions can produce an interference pattern.

Eg. Interference with light transmitted through a "diffraction grating". By measuring the geometry of the interference pattern it is possible to deduce the spacing of the lines on the diffraction grating.

X-Ray Diffraction
The Braggs (father Sir William Henry Bragg and son Sir William Laurence Bragg) adapted this technique to investigating the crystal structure of many solids (in particular, metals). Their general technique is known as "X-ray crystallography".

An X-ray tube emits X-rays onto a sample. The reflected interfering X-rays hit a photographic film, allowing the interference pattern to be seen.

X-rays needed to be used because the incident wavelength must be approximately equal to the atomic spacing.

Applications of this technique yielded much information about the crystal structure of many solids, especially metals.

Bragg's Law is the formula used by the Braggs in their X-ray crystallography: $d\sin\theta = n\lambda$

> Note this same formula can be applied to the laser/diffraction grating experiment described earlier, however in that case *d* = line spacing on the grating.

Analysis of the interference pattern as well as the angles involved therefore allows the calculation of the crystal layer spacing *d*.

§ Explain that metals possess a crystal lattice structure

The Crystal Lattice Structure of Metals

The Braggs established that metals have a *crystal lattice structure*. We know that metals, in general, have only one, two or three electrons in their outer energy shells. These electrons are only loosely bound to the positive ions, causing a lattice of positive ions to be surrounded by a 'sea' of electrons.

§ Identify that the conducting properties of metals are related to the large number of electrons able to drift through their crystal lattice structure

Drift Velocity

Free electrons in metals travel at approximately 0.01c in random motion, colliding with:

- Each other
- Imperfections in the lattice
- Impurities in the lattice

The formula for drift velocity is: $v = \dfrac{I}{nAe}$ $(I = nvAe)$

§ Discuss the relationship between drift velocity and:

If *I* is kept constant, the drift velocity is:

The density of electrons

- Inversely proportional to the density of free electrons *n*;

The cross sectional area of wire

- Inversely proportional to the cross-sectional area *A*;

The electronic charge

- Inversely proportional to the electric charge *e*, which is a constant.

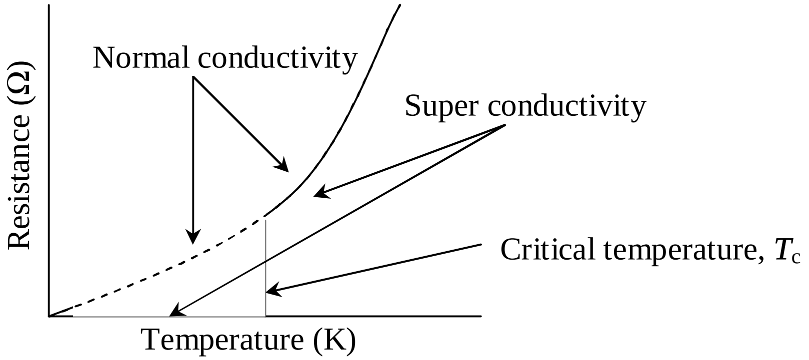
§ Discuss how the lattice impedes the paths of electrons causing heat to be generated

The *collisions of the electrons* cause a loss of *energy* as heat is generated. The collisions are the source of resistance of a wire (*they don't collide with normal ions;* they 'know where they are'). If a lattice has thermal energy (temp > 0 K) then it vibrates, which contributes to the collisions and the resistance of the lattice. If its temperature is reduced, then the vibrations also reduce, lowering the resistance. The resistance of a pure metal drops to zero at 0 K.

§ Identify that superconductors, while still having lattices, allow the electrons to pass through unimpeded with no energy loss at particular temperatures

Limiting conditions:
- *t_c critical temperature*
- *I_c critical current*
- *B_c critical magnetic field*

Superconductors
Some materials, called “superconductors”, achieve zero resistance suddenly at some non-zero temperature, called the “critical temperature” or “transition temperature” (T_c).



§ Explain current theory that suggests that superconductors are conducting materials that, at specific temperatures, force electrons to pair and, through interactions with the crystal lattice, are ultimately able to form an unimpeded orderly stream

The BCS Theory of Superconductivity
This is the Nobel Prize winning theory to explain (type 1) superconductivity from Bardeen, Cooper and Shrieffer.

The theory states that superconductivity is the result of the interaction between electron pairs (called ‘Cooper’ pairs) and vibrations of the crystal lattice:
- A first electron travelling through the lattice attracts the positive ions and this distorts the lattice.
- The distortion creates a concentration of positive charge that attracts a second electron.
- The second electron ‘rides the wave’ behind the first electron.
- The sonic frequency vibration of the lattice forms energy units called ‘phonons’. The exchange of phonon energy from the first to the second electron keeps the cooper pair together for some time.

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

Application of Superconductors

Power Transmission

One of the biggest problems with current power transmission systems is 'joule heating'. The resistance of the cable causes the cable to be heated. This represents a loss of energy. Since $P = I^2R$, the joule heating is proportional to I^2. Hence transformers are used to lower current as much as possible prior to transmission, and this necessitates the use of AC electricity.

If superconductors could be used for transmission cables then their zero resistance means that *no energy would be lost* (i.e. no joule heating).

- Cable of same size could carry 3 to 5 times as much current
- DC is the more logical choice because
  - Don't need to lower current
  - Don't need transformers; and
  - AC involves a slight energy loss

Advantages

- No joule heating, hence energy savings
- This would lower demand for new power stations
- Greater efficiency means less wastage and less demand for fuel, and therefore less environmental impact

Disadvantages

- The cables would need to be kept *very cold*
- Installation costs would be high
- All appliances would need to be redesigned to work on DC
- Current high temperature superconductors are ceramic and therefore too *brittle* to be made into wires

Application of Superconductors

The Meissner Effect:
- *Superconductors resist the penetration of magnetic fields into them*
- *They develop electric currents to make their own B field to push back*
- *This can be used to float a magnet over a superconductor*
- *This "magnetic levitation" idea has been used in Japan to build an experimental **maglev train***

Power Generation

The huge dynamos in a power station can also be made more efficient with superconductors because these use electromagnets to produce the necessary magnetic field. If superconductors were used to make the electromagnets then they would be more *efficient*, making the whole device more efficient.

Power Storage

This is something that is very difficult to do with current technology, and means that power stations must adjust their output to the demand at the time. With superconductors, a long loop can function as a storage device. Current introduced into the loop will *continue to flow around the loop indefinitely*, and can be retrieved when required. A power storage device connected to a power station would allow the station to *run continuously at peak efficiency*, regardless of fluctuations in demand.

Electronics

Most electronics would also become more efficient if built using superconductors. Consider a computer CPU. This is a 70W device, which means that *heat generation is a problem* and a limitation to how fast it can be run. If built using superconductors, this heat problem would be eliminated, allowing the CPU to be run at faster speeds. But how could we replace the semiconductor transistor? In 1962, Brian Josephson invented a superconductor switch that performs the same task as a transistor switch but is *much* faster. This device is called a "Josephson Junction". CPUs built of those would be very much faster than current CPUs.

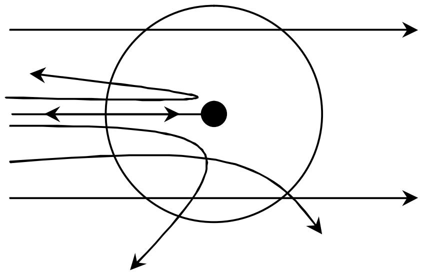
Medical Diagnostics

An MRI machine maps the water molecules inside a person's body to build up a 3D computer image of the person's organs. It does this by having a large superconducting coil that produces an intense magnetic field (4T). The person lies inside the coil. Radio frequency radiation is directed to the patient's body and these conditions cause the H atoms to vibrate. The device picks up the signals produced by the H atoms, works out their locations and maps them.

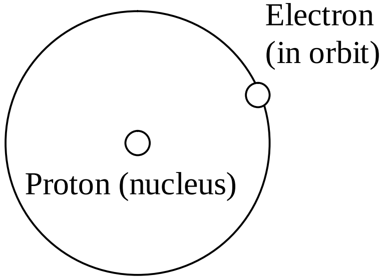
Option Topic: Quanta to Quarks

1. Problems with the Rutherford model of the atom led to the search for a model that would better explain the observed phenomena

- § Discuss the structure of the Rutherford model of the atom, the existence of the nucleus and the electron orbits



Deflection of alpha particles by the nucleus



Rutherford model of the hydrogen atom

J. J. Thomson's Model

The discovery of electrons by Thomson had changed the view on indivisibility of atoms. Thomson was able to determine the charge and mass of electrons and the mass of the electron was found to be 1800 times lighter than the lightest atom, Hydrogen. *He concluded that electrons are sub-atomic*.

He proposed a crude model of the atom, known as the plum-pudding model. Negative electrons are like plums in the positive pudding.

Ernest Rutherford's Alpha Particle Scattering Experiment

- In 1911 Geiger and Marsden, at the instigation of Rutherford, performed an experiment in which the newly discovered *positively charged* alpha particles were fired at a thin gold foil.
- It was observed that most of the alpha particles passed through with only small deflections (as expected with the Thomson model of the atom of the time).
- However it was found that about 1 in 8000 alpha particles deflected back at angles greater than 90°! From this result, Rutherford proposed that the only way that the alpha particles could be deflected through large angles is if *all* the atom's positive charge and nearly all its mass was concentrated in a small dense *nucleus* with the electrons some distance away.
- From the results of the alpha particle scattering experiment, Rutherford was able to show that the atom is *mostly empty space* and was able to estimate the size of the atom and its nucleus.
- He proposed a model where orbiting electrons were held to the positive nucleus by electrostatic attraction. This model was criticised as the physics knowledge of the time suggested an orbiting electron would emit electromagnetic radiation and spiral into the nucleus.

Inadequacies of Rutherford's Atom

Although Rutherford's model successfully explained alpha particle scattering, it left many questions unanswered:

- What is the nucleus made of?
- What keeps the negative electrons from being attracted into the positive nucleus?
- How are the electrons arranged around the nucleus?

§ Analyse the significance of the hydrogen spectrum in the development of Bohr's model of the atom

Niels Bohr's Model of the Atom

Bohr uses Quantum Theory to Explain the Spectrum of Hydrogen:

Bohr knew that, somehow, atoms must produce radiation that formed a characteristic *spectrum* for each element. Bohr realised that the *"atomic oscillators"* of Planck were probably electrons in the atom. The Rutherford model failed to provide any information about the radius of the atom or the orbital frequencies of the electrons.

Bohr was introduced to Balmer's equation for the wavelengths of the spectral lines of hydrogen (*more on this later*), a purely empirical formula at the time. After seeing this equation, Bohr realised how electrons were arranged in the hydrogen atom and also how quantum ideas could be introduced to the atom.

§ Discuss Planck's contribution to the concept of quantised energy

Recall: Planck, Einstein and "Quantised Energy"

Planck interpreted his black body result as meaning that the *"atomic oscillators"* that produced the radiation could vibrate only with certain discrete amounts of energy, ***quanta.*** Einstein later extended this idea to the radiation itself being quantised, ***photons***.

§ Define Bohr's postulates

Spectral Lines of Hydrogen Explained:

The 2^nd postulate explains the line emission spectra. Emission of energy is discontinuous and corresponds to a transition between two stationary states. Since the energy is quantised, the frequency of the emitted radiation is predetermined. A transition between different states will lead to different frequencies i.e. ***colours****.*

Bohr's Postulates

In 1913, Bohr published three papers that addressed the problem of electrons in the Rutherford model and pointed out that the accelerating electrons must lose energy by radiation and collapse into the nucleus. He then applied quantum theory to the atom. To account for the discrepancies between the Rutherford model of the atom and available experimental evidence in particular, the emission spectrum of hydrogen, Bohr proposed three postulates:

1. Electrons in an atom exist in **"stationary states"** in which they possess an unexplainable stability. These states correspond to certain allowed orbits *that allow electrons to revolve without radiating energy*.

2. When an electron falls from a higher energy level to a lower energy level, it emits energy that is *quantised* by the Planck relationship $E_2 - E_1 = \Delta E = \mathrm{h}\,f$

3. **Angular momentum** (mvr) is quantised and can only take values of $\frac{nh}{2p}$ where n is the *principle quantum number.*

§ Describe how Bohr's postulates led to the development of a mathematical model to account for the existence of the hydrogen spectrum:

$$\frac{1}{l} = R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

Other Series of Lines of the Hydrogen Spectrum:

*Lyman series – UV lines with transitions to the **ground state** (n=1)*

*Paschen series – IR lines with transitions to the second **excited state** (n=3)*

Brackett series- IR lines with transitions to the third excited state (n=4)

Pfund series – IR lines with transitions to the fourth excited state (n=5)

The Bohr Model and the Balmer Series

One of the greatest successes of the Bohr model was that it was able to provide a physical basis for the Balmer series formula (which up until that point was purely an empirical formula). Bohr's reasoning was as follows:

From Bohr's 2nd postulate we have:

$$hf = E_f - E_i$$

Bohr was able to derive an expression for the *energy of the orbits* by combining the expression for potential energy of the electron-nucleus system to its kinetic energy, written as:

$E_n = \frac{1}{n^2}E_1$ where n = 1, 2, 3…; E_1 = the energy of the electron in the first energy level = -13.6 eV

From this expression for energy we have:

$E_i = \frac{1}{n_i^2}E_1$ and $E_f = \frac{1}{n_f^2}E_1$ hence:

$hf = \frac{1}{n_f^2}E_1 - \frac{1}{n_i^2}E_1 = \left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)E_1$ and $c = fl \Rightarrow f = \frac{c}{l}$ since: the expression reduces to:

$\frac{1}{l} = \frac{E_1}{hc}\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) = R_H\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$ which is the Balmer formula!
(where R_H is Rydberg's constant = 1.097 * 10^7 m^{-1})

The Hydrogen Atom Explained

We are now able to calculate the wavelengths of the many spectral lines of the hydrogen atom. The original series of the spectral lines was known as the **Balmer series** and contained the four spectral lines in the visible region of the spectrum. These lines correspond to electron jumps to the second lowest energy state, or first excited state, (n = 2) of the hydrogen atom.

Balmer's formula allowed for speculation of the existence of other line series for hydrogen. These were later detected using spectroscopes.

§ Discuss the limitations of the Bohr model of the hydrogen atom

Limitations of the Bohr Model
The Bohr model takes the first step to introduce quantum theory to the hydrogen atom, but has the following limitations:

- **Multi-Electron Atoms:** The Bohr model works reasonably well for atoms with one electron in their outer shell but does not work for any others. It is not possible to calculate the wavelengths of the spectral lines of all other atoms.

- **Relative Intensities of Spectral Lines:** Examination of spectra shows that the spectral lines are not of equal intensity but the Bohr model does not explain why some electron transitions would be favoured over others.

- **Hyperfine Lines:** Careful observations with better instruments showed that there were other lines known as the hyperfine lines. There must be some splitting of the energy levels of the Bohr atom but the Bohr model cannot account for this.

- **Zeeman Effect:** When a gas is excited while in a magnetic field, the emission spectrum produced shows a splitting of the spectral lines (called the *Zeeman effect*). Again, the Bohr model cannot account for this

- **Ad hoc Mixture of Classical and Quantum Physics:** Finally, the Bohr model is a mixture of classical physics and quantum physics and this, in itself, is a problem.

2. The limitations of classical physics gave birth to quantum physics

§ Describe the impact of De Broglie's proposal that any kind of particle has both wave and particle properties

$$E = hf = mc^2$$
$$mc^2 = hf$$
$$mc = \frac{hf}{c}$$
$$\therefore p = \frac{hf}{c}$$

De Broglie's idea initiated the development of quantum mechanics – a complete theory, not a mixture of classical and quantum ideas as used by Bohr.

***Quantum mechanics** is the name given to a set of physical laws that apply to objects the size of atoms or smaller. The concepts of wave-particle duality and uncertainty lie at the heart of quantum mechanics.*

Louis De Broglie's Proposal

In 1923, de Broglie argued that the fact that nobody had managed to perform an experiment that settled once and for all whether light was a wave or a particle was because the two kinds of behaviour are inextricably linked - he made the bold proposal that all particles must have a *wave nature* as well as a *particle nature*.

The expressions for the energy and momentum of light quanta have quantities that are properties of particles on the left-hand side and quantities that are properties of waves on the right-hand side:

$$E = hf$$
$$p = \frac{hf}{c}$$

Electrons had been thought of as well-behaved particles except for the fact that they occupied distinct energy states in the hydrogen atom. These energy states were associated with *integers*. De Broglie was aware of other phenomena in physics that were associated with integers. These included the interference of waves and the vibration of standing waves. He stated: "This fact suggested to me the idea that electrons, too, could not be regarded simply as corpuscles, but that periodicity must be assigned to them."

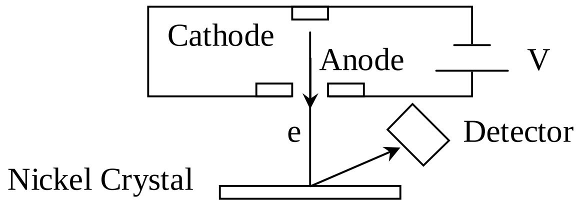
De Broglie described how **matter waves** ought to behave and suggested ways that they could be observed. The wavelength of a photon was Planck's constant divided by its momentum and de Broglie proposed that, similarly, the wavelength of a moving particle would be Planck's constant divided by its momentum. Therefore, photon momentum would be:

$$p = \frac{hf}{c}$$
$$= \frac{h}{l}$$
$$l = \frac{h}{p}$$

The de Broglie wavelength of a particle: $l = \frac{h}{mv}$

§ Describe the confirmation of De Broglie’s proposal by Davisson and Germer

Confirmation of de Broglie’s Proposal by Clinton Davisson and Lester Germer
In 1923, Davisson and Germer proved the wave nature of matter by observing some characteristics of wave properties such as diffraction. Davisson and Germer scattered electrons from the surface of a nickel crystal and obtained an *intensity pattern of the reflected electrons that showed diffraction effects*. This proves that electrons of particle nature also have wave characteristics.



§ Explain the stability of the electron orbits in the Bohr atom using De Broglie’s hypothesis

Bohr’s Stable Electron Orbits Explained
When de Broglie developed the idea of matter waves, he had believed that the orbits of the electron in the hydrogen atom were something like standing waves.

The condition for a standing wave to form on a string fixed at each end is that the length of the string must be an integral number of half-lengths. If we consider an electron as setting up a standing wave pattern as it orbits around a nucleus, there must be an integral number of wavelengths in that pattern. If the circumference is taken as $2\pi r$ then there are n wavelengths in the circumference, $n\lambda = 2\pi r$. From this, and the de Broglie wavelength:

$$l = \frac{h}{mv} = \frac{2pr}{n}$$

$$\frac{nh}{mv} = 2pr$$

$$mvr = \frac{nh}{2p}$$

But this is Bohr’s third postulate – his quantisation condition that angular momentum can exist only integer multiples of $\frac{h}{2p}$

If an integer number of electron wavelengths fit into the circumference of the electron orbit, standing waves could be possible and hence no energy would be lost.

3. Today, quantum physics is used in a range of technologies, including electron microscopes

§ Outline the application of the wave characteristics of electrons in the electron microscope

Electron Microscopes

Because electrons have a much smaller wavelength than light, they produce much less diffraction than light. The diffraction effects of electrons in an electron microscope are therefore much smaller than those of light in an optical microscope. Electrons, therefore, have a much better resolving power than light and electron microscopes makes use of this reduced diffraction to produce images which are of much higher magnification than is possible with light.

Electron microscopes do not take advantage of the wave nature of electrons to focus the electrons. In the ‘lenses’ of an electron microscope it is the particle nature of electrons that is important. Electrons are focused by deflection by electric or magnetic fields. The forces that produce this deflection depend on the particle nature of the electrons.

In all electron microscopes:
- An *electron source* produces a stream of electrons that are accelerated towards the specimen by an accelerating potential difference.
- Metal *apertures* and *magnetic lenses* confine and focus the electron beam.
- Other *magnetic lenses* focus the beam on the specimen.
- Interactions inside the specimen affect the electron beam. These effects are converted into an image.

Because air will deflect electrons, the interior of electron microscopes is under a high vacuum which means that the specimens must be dead – a definite disadvantage to light microscopes. However, electron microscopes can magnify up to a million times, which is a major advantage.

§ Discuss the relationships in electron microscopes between the electrons, magnetic lenses and refraction

Magnetic Lenses
Recall that a charge particle moving in a magnetic field experiences a force. By passing an electron beam through a set of high-powered magnets, the beam can be focussed.

Electromagnetic lenses consist of a *solenoid* with magnetic *pole pieces* that concentrate and determine the shape of the field.

In optical microscopes the glass lenses have a fixed focus and the specimen is moved towards or away from the objective lens to bring it into focus. In electron microscopes, the electromagnetic lenses have a variable focus and the specimen to objective distance is kept constant.

Magnification is achieved by varying the current in the objective lens coil.

Types of Electron Microscopes
The early electron microscopes were *transmission electron microscope* types (TEM) in which the electrons passed through the specimen. They are analogous to transmission light microscopes.

A later development (1942) was the *scanning electron microscope* (SEM) which can produce a three-dimensional image of the specimen by reflection of the electrons off the specimen. These are analogous to reflecting light microscopes.

4. The work of Chadwick and Fermi in producing artificial transmutations led to practical applications of radiation

- Identify the importance of conservation laws to Chadwick's discovery of the neutron

Rutherford Predicts the Neutron
In 1920, Rutherford proposed that a neutral particle with similar mass to the proton – which he termed the neutron – might exist in the nucleus.

This particle should be a combination of a proton and have a mass slightly larger than that of a proton. The neutron's neutral charge would not affect the nucleus' charge and the extra mass would account for the measured mass of the nucleus.

The problem was that the particle would be electrical neutral and extremely difficult to detect because it would not leave tracks in cloud chambers or bend in electric and magnetic fields.

The Conservation Laws which apply to Atoms
There are a number of quantities in chemical and nuclear changes, which, *in total* remain unchanged throughout the process.

Charge is Conserved (Atomic Number Z)
During a nuclear or chemical reaction, the total charge of all the reactants equals the total charge of all the products.

Mass Number A is Conserved
The total number of protons + neutrons remains the same during a reaction.

Mass / Energy is Conserved
The total mass or energy equivalence of mass (by $E = mc^2$) during a reaction remains the same. This means during a nuclear reaction, mass / energy cannot be created or destroyed.

James Chadwick discovers the Neutron
In 1930, the Germans Walther Bothe and Becker discovered that bombarding beryllium with alpha particles resulted in the emission of a penetrating type of radiation. The radiation seemed to be *similar to gamma rays but it was much more highly penetrating*.

In France, Frederic Joliot and Irene Curie studied this radiation falling on a block of paraffin (paraffin is a hydrocarbon rich in hydrogen atoms). They found that the radiation knocked protons (hydrogen nuclei) from the paraffin. Now that charged particles were involved, it was much easier to determine their properties. The high energy of the protons emitted (5 MeV) was a problem because applying the *conservation of energy and conservation of momentum* to the collision between a gamma ray and a proton yielded a value for the incident gamma ray of at least 50 MeV. This was a major dilemma because the energy of the incident alpha particles was only about 5 MeV.

In 1932, Chadwick suggested that this radiation consisted of Rutherford's *neutrons* and not gamma rays. By applying the *laws of conservation of momentum and energy*, Chadwick was able to prove the existence of the neutron: ${}^{9}_{4}Be + {}^{4}_{2}He \rightarrow {}^{12}_{6}C + {}^{1}_{0}n$

§ Define the contents of the nucleus (protons and neutrons) as nucleons and contrast their properties

Nucleons are particles that normally reside in the nucleus. These are collectively ***protons and neutrons***.

Nucleon	Rest mass (kg)	Charge (coulomb)
Proton	1.673×10^{-27} kg	$+1.6 \times 10^{-19}$ C (=e)
Neutron	1.675×10^{-27} kg	neutral

§ Define the term 'transmutation'

Transmutation

Transmutation occurs when one element changes into another. In all transmutations, the mass number and atomic number are conserved.

§ Define Fermi's experimental observation of nuclear fission and his demonstration of a nuclear chain reaction

Enrico Fermi Discovers Nuclear Fission

Between 1934 and 1938, Fermi bombarded many of the known elements as possible with the newly discovered neutrons. The neutron, because of its neutral nature, proved to be better at causing transmutations than alpha particles, which are repelled by the positive nucleus by their positive charge. In the majority of cases, *new isotopes were formed*. Occasionally this new nucleus was radioactive and emitted a beta particle.

Nuclear Fission

Fission is a transmutation process where particle bombardment of heavy atoms causes them to lose stability and split randomly into two large isotopes plus a number of smaller particles, which are usually neutrons. The two isotopes formed usually have too many neutrons and are radioactive.

When Fermi reached uranium (the heaviest known element, 92), it was hoped that the uranium would undergo beta decay to form an isotope of element number 93 – the first *transuranic element*.

$${}^{238}_{92}U + {}^{1}_{0}n \rightarrow {}^{239}_{92}U \qquad {}^{239}_{92}U \rightarrow {}^{239}_{93}Np + {}^{0}_{-1}e$$

Although this occurred, it was found that there were at least four different products which emitted betas with different measurable half-lives. What was eventually found was that uranium is a mixture of isotopes U-235, U-238 and U-233. The U-235 isotope was reacting, absorbing the neutron and forming an unstable isotope that split into two roughly equal halves – *nuclear fission*.

$${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3{}^{1}_{0}n + g$$

Fermi and Chain Reaction

For the fission of U-235, it can be noted that more neutrons are produced than used. This opens the possibility of a single neutron causing a *chain of atoms* to react.

§ Identify that Pauli's suggestion of the existence of neutrino is related to the need to account for the energy distribution of electrons emitted in β-Decay

Pauli and the Neutrino
All alpha particles emitted from a particular radioactive species have the same energy but beta particles seem to be emitted with a range of energies. There was considerable debate as to whether the beta particles had a continuous or line spectrum.

The question was asked, how could one beta decay be associated with emission of a certain amount of energy from a nucleus but another beta decay from a similar nucleus be associated with a different amount of energy? After all, both decays produced the same new nucleus.

In 1931, in an attempt to resolve the paradoxes involving beta decay, Pauli proposed that another particle, the *neutrino*, was emitted during beta decay.

${}_{0}^{1}n \rightarrow {}_{1}^{1}p + {}_{-1}^{0}e + {}_{0}^{0}\bar{v}$ beta-minus decay (neutron à proton + electron + antineutrino)

${}_{1}^{1}p \rightarrow {}_{0}^{1}n + {}_{+1}^{0}\bar{e} + {}_{0}^{0}v$ beta-plus decay (proton à neutron + positron + neutrino)

Fermi proposed that the number of electrons and neutrinos was not constant. Electrons and neutrinos could be created or disappear just like photons. The assumption that another small neutral particle was forming allowed the sum of the particles on both sides of the equations to be equal in mass/energies.

§ Describe nuclear transmutations due to natural radioactivity

Artificial Transmutations
Particles are fired into nuclei to make it unstable. This causes it to undergo a nuclear reaction (i.e. a transmutation) e.g. nuclear fission.

Nuclear Transmutations due to Natural Radioactivity
Natural transmutations occur in radioactive decay such as alpha and beta decay.

Alpha Decay ${}_{Z}^{A}X \rightarrow {}_{Z-2}^{A-4}Y + {}_{2}^{4}He$

Beta Decay b^{-} decay : ${}_{Z}^{A}X \rightarrow {}_{Z+1}^{A}Y + {}_{-1}^{0}e + {}_{0}^{0}\bar{v}$ b^{+} decay : ${}_{Z}^{A}X \rightarrow {}_{Z-1}^{A}Y + {}_{+1}^{0}e + {}_{0}^{0}v$

Gamma Decay ${}_{Z}^{A}X^{*} \rightarrow {}_{Z}^{A}X + g$

where * denotes an excited nucleus.

§ Evaluate the relative contributions of electrostatic and gravitational forces between nucleons

Forces Holding the Nuclear Together
Protons in the nucleus should repel each other violently through coulombic repulsion.

Coulombic force of repulsion between protons

$$F_E = 9\times10^9 \frac{q_1 q_2}{r^2}$$ where $r = 10^{-15}$ m; q = e = 1.6×10^{-19} C

Gravitational attraction between protons

$$F_G = 6.67\times10^{-11} \frac{m_1 m_2}{r^2}$$ where $r = 10^{-15}$ m; $m = 1.672 \times 10^{-27}$ kg

Upon calculation, it can be seen the gravitational force is so small as to be insignificant when compared to the electrostatic repulsion between protons.

§ Account for the need for the strong nuclear force and describe its properties

The Strong Nuclear Force
The strong nuclear force exists between any two nucleons and acts against the electrostatic repulsion between protons. It is only strong at very close range ie. the protons and neutrons have to be *very close together to attract*. Otherwise the protons will repel. Overcoming this repulsive force before the nuclei are close enough to attract explains the difficulty in combining atoms (*nuclear fusion*).

Strong nuclear force acts between:	**Electrostatic repulsion acts between:**
proton-proton	proton-proton
proton-neutron	
neutron-neutron	

Heavier nuclei need more neutrons to remain stable as they add extra strong nuclear force without adding extra electrostatic repulsion.

§ Explain the concept of a mass defect using Einstein's equivalence between mass and energy

Binding Energy is the energy equivalent of mass defect according to $E = mc^2$. It is the energy needed to separate the atom into its separate parts.

Mass Defect is the difference between the mass of a nucleus and the sum of the masses of its individual parts.

The existence of binding energy implies that the making of atomic nuclei from their particles causes a mass drop and emission of energy. The concept of binding energy has another aspect. Breaking an atom into its particles requires energy.

Using $E = mc^2$, binding energy (*MeV*) = 931.5 x mass defect (*u*)
where: 1 ***u*** = 1.661×10^{-27} kg;
1 ***MeV*** = 1.602×10^{-13} J

Binding Energy Per Nucleon
This is a very good indicator of nuclear stability. Any nuclear reaction that produces daughter nuclei with higher BE/nucleon than the reactant has increased the total Be/nucleon, which means that energy is given off by the reaction. There are two types of reactions that do this:

1. Nuclear fission of heavy nuclei
2. Nuclear fusion of light nuclei

§ Compare requirements for a controlled and uncontrolled nuclear chain reaction

Controlled and Uncontrolled Chain Reactions
In a controlled chain reaction, only one neutron from each fission is available to split another uranium atom. Surplus neutrons are absorbed by control rods made of materials such as cadmium (that absorb neutrons without undergoing fission) to keep the rate of fission steady.

In an uncontrolled chain reaction, each neutron released by the uranium atom as it splits is allowed to hit another uranium atom. There is a rapid build up of atoms undergoing fission and a rapid release of energy.

5. An understanding of the nucleus has led to large science projects and many applications

§ Explain the basic principles of a fission reactor

Radioisotopes
Radioisotopes are produced artificially in nuclear reactors either as fission products or by neutron bombardment of materials placed in the reactor for transmutation.

Nuclear Fission Reactors
Nuclear fission reactors for power stations are used as a heat source to boil water to produce pressurised steam to drive a turbine/dynamo to generate electricity.

Every reactor needs:
- <u>Fuel Rods</u> – consist of fissionable material such as U-235 (most uranium is U-238)
- <u>Control Rods</u> – absorb neutrons to slow down reaction rate (eg. cadmium or boron)
- <u>Moderator</u> – slows down neutrons by collision (eg. heavy water, graphite). Fast neutrons are produced by the reactions but slow neutrons are more effective at triggering new reactions
- <u>Coolant</u> – removes the heat produced by the reactor (to prevent fire) and to use it to boil water to produce the steam to drive the turbines
- <u>Criticality</u> – a reactor must be a certain size before a controlled chain reaction is possible
- <u>Start Up</u> – To produce fission, a source of neutrons is necessary. The best way is to use the Chadwick method and use Radium to bombard Beryllium with alphas to produce neutrons.

Once the reaction commences, fuel rods are loaded in one by one and control rods are drawn after each loading in an attempt to reach criticality.

§ Describe some medical and industrial applications of radio-isotopes

Applications of Radioisotopes
Medical and industrial applications of radioisotopes include medical diagnosis by radioactive tracing, cancer treatment by radiotherapy, sterilisation, tracing, and attenuation.

§ Explain why neutron scattering is used as a probe by referring to the properties of neutrons

Neutron Scattering
Neutron scattering is a powerful method of analysing the internal structure and properties of matter using neutrons. Like all atomic particles, neutrons demonstrate wave characteristics and form *diffraction patterns*. Their particular value is found in their lack of charge. This allows them to penetrate atoms to a great degree than electrons or even X-rays. Neutron scattering works particularly well for materials containing *light atoms such as hydrogen*. This includes many organic substances. The technique aided the analysis and developments of better automobile exhaust catalysts, magnetic materials in computer data storage devices and new superconducting materials. It even helped in the study of pathogenic viruses.

6. Our attempts to understand the structure of matter is an ongoing process

§ Identify the ways by which physicists continue to develop their understanding of matter, including:

- The use of accelerators as a probe to investigate the structure of matter
- The key features and components of the standard model of matter, including quarks and leptons
- The links between high energy particle physics and cosmology

Particle Accelerators
Particle accelerators are one of the main tools used to create and measure the small particles that make up atoms. They act by accelerating charged particles to quite high speeds before smashing them into a target of atoms. The products often form tracks that can be photographed as they spiral around a cloud chamber and form other particles by radioactive decay.

Linear Accelerators
An electron, a proton, or a heavy-ion accelerator in which the paths of the particles accelerated are essentially straight lines rather than circles or spirals.

Cyclotrons
A circular particle accelerator in which charged subatomic particles generated at a central source are accelerated spirally outward in a plane perpendicular to a fixed magnetic field by an alternating electric field. A cyclotron is capable of generating particle energies between a few million and several tens of millions of electron volts.

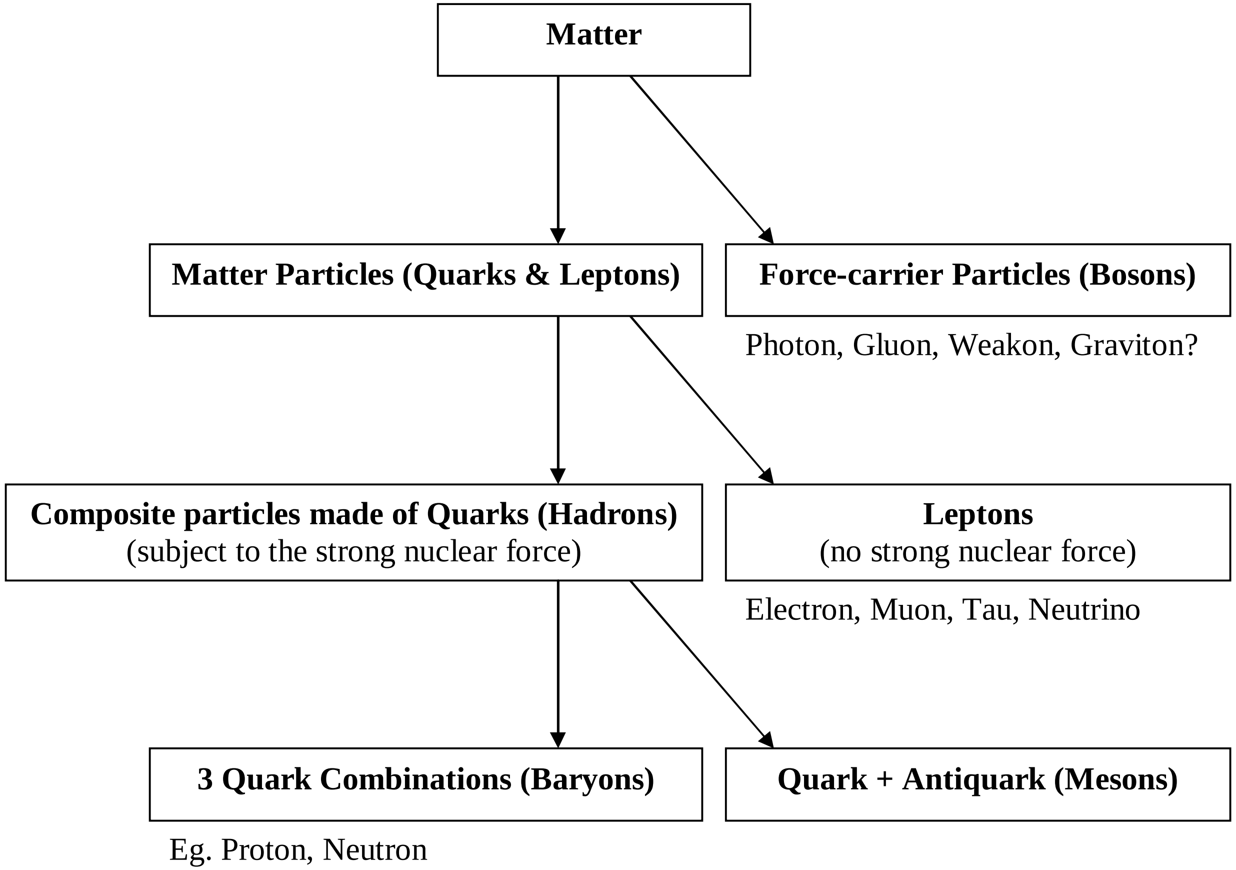
Synchrotrons
An accelerator in which charged particles are accelerated around a fixed circular path by an electric field and held to the path by an increasing magnetic field.

The Standard Model of Matter

The Standard Model of particle physics is a mathematical description of all known particles and the forces between them. It enables us to explain all the behaviour of these particles. A very close interplay between experimental and theoretical physics prompted the development of the Standard Model.

The standard model has two main components to explain the **fundamental forces**:
The electroweak theory: This describes interactions through the electromagnetic and weak forces.
Quantum chromodynamics: This is the theory of the strong force.
(Gravity is not part of the standard model.)

There are **three families under which matter is grouped –** quarks, leptons and bosons.
Matter particles: These are fundamental particles. They are the quarks and leptons.
Force-carrier particles: Each type of fundamental force is caused by the exchange of force-carrier particles. These are the fundamental (or gauge) bosons. They include phons and gluons.



High-energy Particle Physics and Cosmology

Many questions about astronomy and the Standard Model are still being asked. Will the Standard Model be able to deal with some of the latest discoveries from astronomy?

Dark Matter

Research into astronomy has led to the prediction of "dark matter" as an important constituent of the universe. What is this dark matter? It seems as if it may be different from any matter we have experienced. Does it consist of so far undiscovered fundamental particles? If so, will they fit into the Standard Model?

Dark Energy

Another recent discovery from astronomy is that the universe is expanding at an increasing rate. The term "dark energy" has been applied to a type of matter, which has a repulsive rather than attractive gravitational force. Is the universe really expanding at an increased rate and if it is, what does that really mean in terms of matter in the universe?

As research into the most fundamental aspects of matter developed, it became linked to research in cosmology and the origins of the universe. The important questions about the universe on a very large scale and on the very smallest scale are intertwined.

Time from Bang	Temp. (K)	Event
10^{-18} sec	10^{15} K	Decoupling of weak-force bosons (weakons)
10^{-12} sec	10^{14} K	Matter and antimatter baryons appear and fight a war of annihilation. Because of a slight surplus of matter particles, the matter dominates
10^{-5} sec	10^{13} K	Decoupling of neutrinos
10^{-3} sec	10^{11} K	War of annihilation between electrons and positrons (antimatter). Electrons win
10^{4} years	10^{5} K	Matter particles dominate radiation particles. Atomic nuclei such as He form
10^{9} years	2.5 K	Galaxies and quasars form