# 3.1 Measurements and their errors

## 3.1.1 Use of SI units and their prefixes

- SI units

| Quantity | Unit | Symbol |
|---|---|---|
| **Mass** | kilogram | kg |
| **Length** | metre | m |
| **Time** | second | s |
| **Current** | ampere | A |
| **Temperature** | kelvin | K |
| **Amount of substance** | mole | mol |

- Prefixes

| Name | Symbol | Multiplier |
|---|---|---|
| Tera | T | $10^{12}$ |
| Giga | G | $10^{9}$ |
| Mega | M | $10^{6}$ |
| Kilo | k | $10^{3}$ |
| Centi | c | $10^{-2}$ |
| Milli | m | $10^{-3}$ |
| Micro | μ | $10^{-6}$ |
| Nano | n | $10^{-9}$ |
| Pico | p | $10^{-12}$ |
| Femto | f | $10^{-15}$ |

## 3.1.2 Limitation of physical measurements

- Definitions

| Term | Definition |
|---|---|
| **Precision of a measurement** | Precise measurements = very little spread about the mean value. Depends only on the extend of random error |
| **Precision of an instrument / resolution** | The smallest non-zero reading that can be measured |
| **Repeatability** | If the original experimenter can redo the experiment with the same equipment and method and get the same results it is repeatable |
| **Reproducibility** | If the experiment is redone by a different person or with different techniques and equipment and the same results are found, it is reproducible |
| **Accuracy** | How close a measurement or answer is to the true value |

- Types of errors
  - Random errors
    - Affect precision, cause differences in measurements

    - Cannot get rid of all random errors
    - Reducing random errors
      - Take at least 3 repeats and calculate a mean
      - Use computers/data loggers/cameras to reduce human error and enable smaller intervals
      - Use appropriate equipment
  - Systematic errors
    - Affect accuracy
    - Occur due to the apparatus or faults in the experimental method
    - Causes all results to be too high or too low by the **same amount** each time
    - Types
      - Zero error: balance not zeroed correctly (all increase / decrease by the same amount)
      - Parallax error: reading the scale at a different angle than parallel
    - Reducing systematic errors
      - Calibrate the apparatus by measuring a known value
      - Correct for background radiation for radiation experiments
      - Read the meniscus at eye level
      - Use controls in experiments
- Uncertainty of measurements
  - The bounds in which the accurate value can be expected to lie
  - Absolute uncertainty: uncertainty given as a fixed quantity e.g. $7 \pm 0.6$ V
  - Fractional uncertainty: uncertainty as a fraction of the measurement e.g. $7 \pm \frac{3}{35}$ V
  - Percentage uncertainty: uncertainty as a percentage of the measurement e.g. $7 \pm 8.6\%$ V
  - To reduce percentage and fractional uncertainty: measure larger quantities
  - Uncertainty can only be quoted to the **same precision** as the **measuring instrument / same number of decimal places as the data**
  - Work out uncertainty from the **number of decimal places** if not specified
- Reading
  - 1 value is found
  - Uncertainty in reading = $\pm$ smallest division
- Measurement
  - The difference between 2 values are found
  - Uncertainty in measurement = $\pm$ 2 × smallest division
- Uncertainty in different situations
  - Digital readings: uncertainty quoted or assumed to be $\pm$ the last significant digit
  - Repeated data: uncertainty = $\pm \frac{\text{range}}{2}$
- Uncertainty calculations
  - Adding / subtracting data = add absolute uncertainties
  - Multiplying / dividing data = add percentage uncertainties
  - Raising to a power = multiply percentage uncertainty by power
  - Uncertainties given to the same number of sig figs as the data
- Uncertainties on graphs
  - Uncertainties shown as error bars on graphs
  - A line of best fit on a graph should go through all error bars (excluding anomalous points)
- Uncertainty of gradient of line of best fit
  - Draw a steepest and shallowest line of worst fit (must go through all error bars)
  - Calculate the gradient of the line of best and worst fir
  - The uncertainty is the difference between the best gradient and the worst gradient (the one with the greatest difference in magnitude from the 'best' line of best fit)
  - $\text{percentage uncertainty} = \frac{|\text{best gradient} - \text{worst gradient}|}{\text{best gradient}} \times 100\%$
    $= \frac{\text{maximum gradient} - \text{minimum gradient}}{2} \times 100\%$
- Uncertainty of x and y-intercept

- $\text{percentage uncertainty} = \frac{|\text{best y intercept} - \text{worst y intercept}|}{\text{best y intercept}} \times 100\%$
  $= \frac{\text{maximum y intercept} - \text{minimum y intercept}}{2} \times 100\%$

### 3.1.3 Estimation of physical quantities

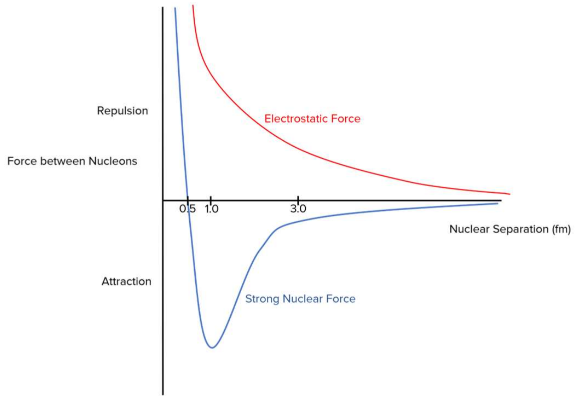
- Orders of magnitude
  - Powers of 10 which describe the size of an object
  - Give a value to the nearest order of magnitude = round to the nearest order of magnitude

# 3.2.1 Particles

## 3.2.1.1 Constituents of the atom

- Constituents of an atom
  - | Particle | Charge (C) | Relative charge | Mass (kg) | Relative Mass | Specific Charge ($Ckg^{-1}$) |
    |---|---|---|---|---|---|
    | **Proton** | $+1.6 \times 10^{-19}$ | +1 | $1.67(3) \times 10^{-27}$ | 1 | $9.58\times10^{7}$ |
    | **Neutron** | 0 | 0 | $1.67(5) \times 10^{-27}$ | 1 | 0 |
    | **Electron** | $-1.6 \times 10^{-19}$ | -1 | $9.11\times10^{-31}$ | 0.0005 | $1.76\times10^{11}$ |
- Specific charge
  - $\text{specific charge} = \dfrac{\text{charge}}{\text{mass}}$
  - Unit = C $kg^{-1}$
- Nuclide notation
  - ${}^{A}_{Z}X$
  - A = nucleon / mass number = number of protons + number of neutrons
  - Z = proton / atomic number = number of protons
  - X = symbol for the element
- Isotopes
  - Atoms with the same number of protons but different numbers of neutrons
- Nuclide
  - A type of nucleus

## 3.2.1.2 Stable and unstable nuclei

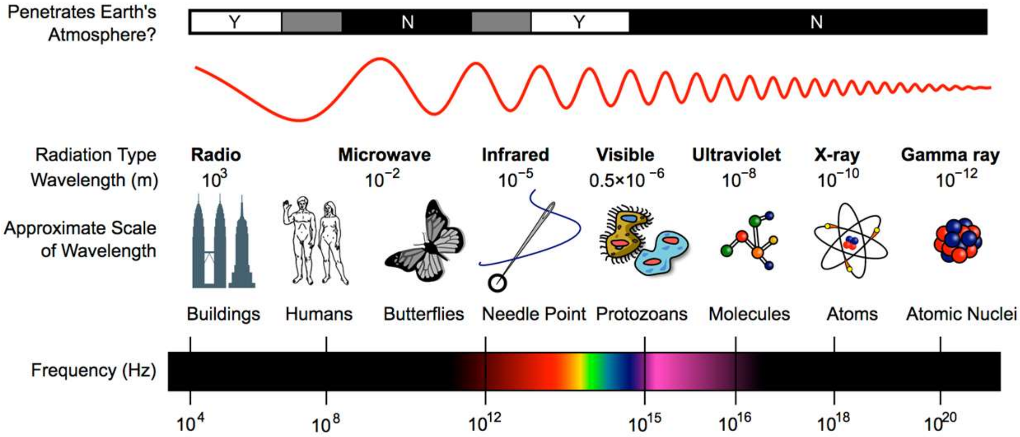
- The strong nuclear force (SNF)
  - One of the 4 fundamental forces of nature
  - Keeps the nucleus stable by counteracting the electrostatic force of repulsion between protons in the nucleus and keeping protons and neutrons together
  - Only acts on nucleons, has a very short range
    - Short-range attraction up to separation of 3 fm (1 fm = $10^{-15}$ m)
    - Very-short range repulsion for separations less than about 0.5 fm
    - 

- Unstable nuclei
  - Too many protons / neutrons / both
  - SNF not enough to keep them stable
  - Decay in order to become stable (type depends on the amount of each nucleon)
- Alpha decay
  - **Too many protons and neutrons**
  - Alpha particle emitted
  - ${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha$
- Beta-minus decay
  - **Too many neutrons** (neutron-rich)
  - A neutron changes into a proton

- Fast-moving electron (beta particle) + an antineutrino (antiparticle with no charge) emitted
- ${}^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + {}_{-1}^{0}\beta + \bar{v}$

- Neutrino ($\bar{v}$)
  - At first scientists believed that only an electron was emitted from the nucleus during beta-minus decay
  - Observation of energy levels before + after decay showed that energy was not conserved (some energy was lost)
  - Neutrinos were hypothesised for the loss of energy and later observed

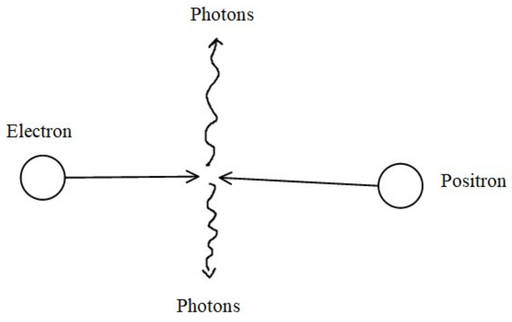
## 3.2.1.3 Particles, antiparticles and photons

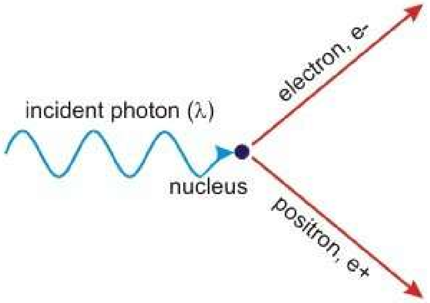
- EM waves
  - Emitted by a charged particle when it loses energy
    - When a fast-moving electron is stopped / slows down / changes direction
    - When an electron in a shell of an atom moves to a different shell of lower energy
  - 


- Photon model of EM radiation
  - EM waves are emitted as short burst of waves
  - Each burst = a packet of EM waves = a proton
  - Photons transfer energy and have <u>no mass</u>
  - The energy of photons is directly proportional to the frequency of EM radiation
    - $E = hf = \dfrac{hc}{\lambda}$
    - $h$ = Planck constant = $6.63 \times 10^{-34}$ Js
- Rest energy
  - Unit = MeV (millions of electron volts) = $1.60 \times 10^{-13}$ J
  - 1 electron volt = the energy transferred when an electron is moved through a p.d. of 1 V
  - 1 eV = $1.60 \times 10^{-19}$ J
- Antiparticle
  - Same rest energy and mass as the particle but all other properties are opposite
  - For every type of particle there is an antiparticle
- Types of antiparticles

| Particle | Antiparticle |
|---|---|
| **Electron** | Positron |
| **Proton** | Antiproton |
| **Neutron** | Antineutron |
| **Neutrino** | Antineutrino |

- Annihilation
  - Where a particle and a corresponding antiparticle meet and their mass is converted into radiation energy
  - Two photons moving in opposite directions are produced in the process so momentum is conserved

- 

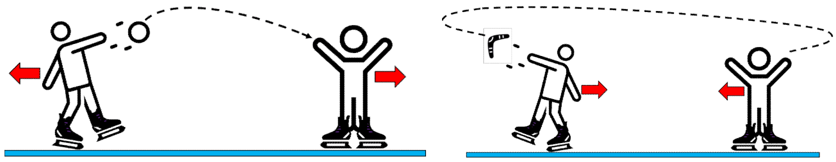
- PET scanner
  - Position emission topography
  - Allows 3D images of the inside of the body to be taken
  - Position-emitting isotope administered to patient, some reach the brain via the blood system
  - As positions are released they annihilate with electrons already in the patients system
  - Two gamma photons released for each annihilation which can be easily detected
  - Image built up gradually
- Pair production
  - A photon is converted into a particle and a corresponding antiparticle
  - Can only occur when the photon has an energy greater than the total rest energy of both particles
    - Minimum energy of a photon needed, $hf_{\text{min}}$ = 2 × rest energy = 2$E_0$
  - Excess energy = converted into KE of particles
  - 


## 3.2.1.4 Particle interactions

- Four fundamental interactions
  - Gravity
  - Electromagnetic
  - Weak nuclear
  - Strong nuclear / strong interaction
- Exchange particles model
  - Forces between particles are caused by exchange particles (force carriers)
  - Exchange particles carry energy and momentum between the particles experiencing the force
  - Each fundamental force has its own exchange particles
    - 

| Interaction | Exchange particle / gauge bosons | Range (m) | Acts on | Strength |
|---|---|---|---|---|
| **Strong nuclear** | Pions (particles)<br>Gluon (quarks) | $10^{-15}$ | Hadrons | Strongest |
| **Weak nuclear** | W boson ($W^+$ or $W^-$) | $10^{-18}$ | All particles | 2nd weakest |
| **EM** | Virtual photon ($\gamma$) | Infinite | Charged particles | 2nd strongest |
| **Gravity** | *Graviton | Infinite | Particles with mass | Weakest |

  - Momentum transferred from one particle to another

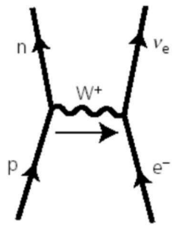
- 

  **Repel** **Attract**

- The weak nuclear force
  - Responsible for beta decay, electron capture and electron-proton collisions
  - Exchange particles = W bosons ($W^+$ or $W^-$)
    - Non-zero rest mass
    - Very short range $\leq$ 0.001 fm
    - Positively or negatively charged
- Electron capture / electron-proton collisions
  - Same equation + different exchange particle
  - $p + e^- \rightarrow n + v_e$

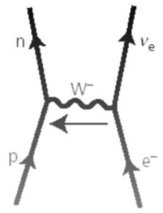
    Electron capture

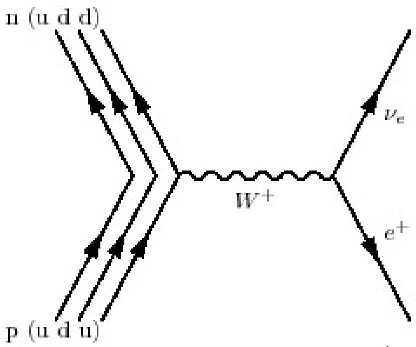
    $p + e^- \rightarrow n + v_e$

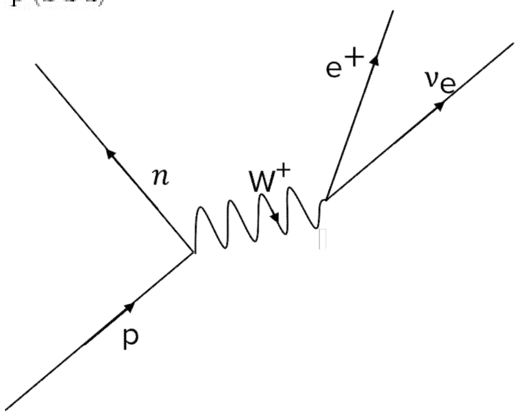
    


  - Proton – electron collision

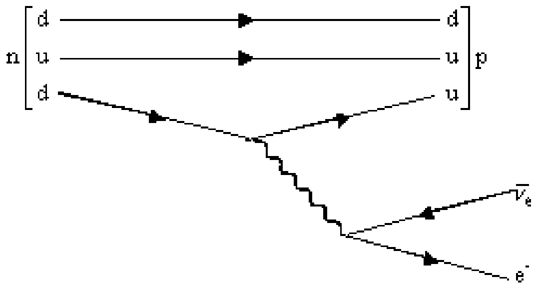
    $p + e^- \rightarrow n + v_e$

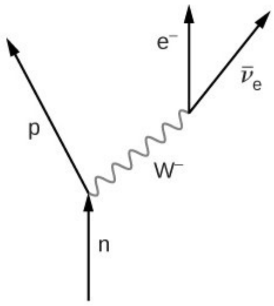
    

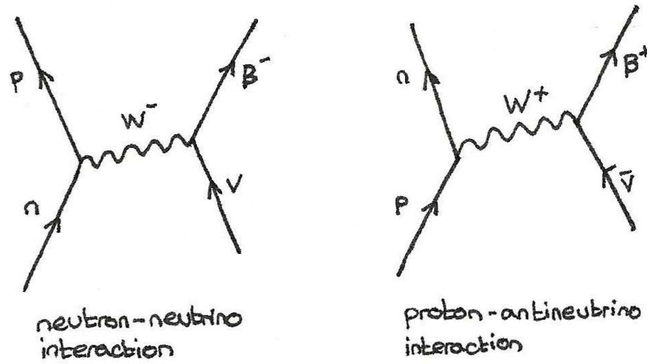

- Beta-plus / beta-minus decay
  - Beta-plus: $p \rightarrow n + e^+ + v_e$
    - 

    - 

  - Beta-minus: $n \rightarrow p + e^- + \overline{v_e}$

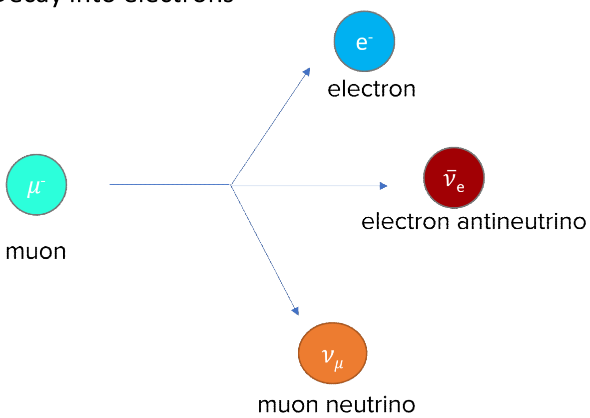
    - 

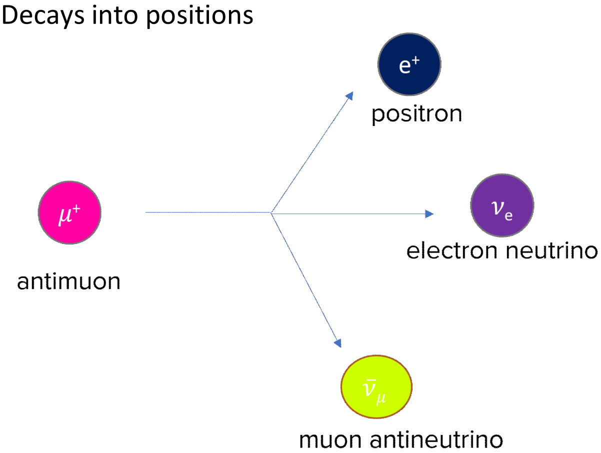
    - 


- Other W boson interactions
  - 


## 3.2.1.5 Classification of particles

- Classifying particles
  - All particles are either hadrons or leptons
  - Leptons = fundamental particles, cannot be broken down any further + do not experience SNF
  - Hadrons = formed of quarks (fundamental particles), experiences SNF, tend to decay through weak interaction
  - Both experience weak interaction, gravitational interaction and electromagnetic interaction (if charged)
- Types of hadrons
  - Baryons / antibaryons
    - Formed of 3 quarks / antiquarks
    - Protons and all hadrons (incl. neutrons) that <u>eventually decay into protons</u>
    - Baryons = protons, neutrons, etc., antibaryons = antiprotons, antineutrons, etc.
  - Mesons
    - Formed of 1 quark + 1 antiquark
    - Hadrons that <u>do not include protons</u> in their decay products
    - Pion / π meson
      - The lightest and most stable meson
      - Produced in high energy particle collisions, discovered in cosmic rays
      - Exchange particle for SNF
      - Different charges: $\pi^+$, $\pi^-$, $\pi^0$
    - Kaon / K meson
      - Heavier + less stable
      - Produced by the strong interaction between pions and protons
      - Eventually decay into pions (many possibilities)
      - Different charges: $K^+$, $K^0$, $K^-$
- Baryon number

- 1 = baryon, -1 = antibaryon, 0 = not a baryon
  - A quantum number
  - Always conserved in particle interactions
- Proton
  - The only stable baryon
  - All baryons will eventually decay into a proton
- Types of leptons
  - Electron
    - Stable
    - Relative charge = -1
    - Neutrino = electron neutrino
  - Muon / ų$^-$
    - Heavier than electrons
    - More unstable
    - Relative change = -1
    - Neutrino = muon neutrino
    - Decay into electrons
    - 

  - Neutrinos / $v_e$, $v_u$
    - Negligible mass
    - 0 charge
    - Only interact through weak interaction
    - The most abundant leptons in the universe
  - Antimuon / ų$^+$
    - Decays into positions
    - 

- Lepton number
  - Gives the number of leptons
  - 1 = lepton, -1 = antilepton, 0 = not a lepton
  - 2 types
    - Electron lepton number: +1 for electrons and electron neutrinos, and -1 for positrons and electron antineutrinos
    - Muon lepton number: +1 for muons and muon neutrinos, and -1 for anti-muons and muon antineutrinos
    - Both conserved during reactions

- Strangeness
  - A quantum number
  - Reflect the fact that strange particles are always created in pairs
  - Always conserved in strong interactions
  - Change by 0, +1 or -1 in weak interactions
- Strange particles
  - Particles which are produced by the strong nuclear interaction but decay by the weak interaction
  - Strange particles are created in twos
  - e.g. kaons (decay into pions through the weak interaction), assume all others are non-strange particles
- Investigating particle physics
  - Particle accelerators may be built
  - These are very expensive + produce huge amounts of data
  - Scientific investigations rely on collaboration of scientists internationally

## 3.2.1.6 Quarks and antiquarks

- Properties of quarks

| Quark particle | Charge *Q* | Strangeness *S* | Baryon number *B* |
|---|---|---|---|
| **Up** $\mathrm{u}$ | +2/3 | 0 | +1/3 |
| **Down** $\mathrm{d}$ | -1/3 | 0 | +1/3 |
| **Strange** $\mathrm{s}$ | -1/3 | -1 | +1/3 |

- Properties of antiquarks

| Antiquark particle | Charge *Q* | Strangeness *S* | Baryon number *B* |
|---|---|---|---|
| **Up** $\overline{\mathrm{u}}$ | -2/3 | 0 | -1/3 |
| **Down** $\overline{\mathrm{d}}$ | +1/3 | 0 | -1/3 |
| **Strange** $\overline{\mathrm{s}}$ | +1/3 | +1 | -1/3 |

- Combination of quarks and antiquarks in baryons / antibaryons

| Particle | Combination | Baryon number |
|---|---|---|
| **Proton** | $\mathrm{uud}$ | 1 |
| **Neutron** | $\mathrm{udd}$ | 1 |
| **Antiproton** | $\overline{\mathrm{u}}\overline{\mathrm{u}}\overline{\mathrm{d}}$ | -1 |
| **Antineutron** | $\overline{\mathrm{u}}\overline{\mathrm{d}}\overline{\mathrm{d}}$ | -1 |

- Combination of quarks and antiquarks in mesons

| Particle | Combination | Charge (e) | Strangeness | Baryon number |
|---|---|---|---|---|
| $\pi^0$ | $\mathrm{u}\overline{\mathrm{u}}$ or $\mathrm{d}\overline{\mathrm{d}}$ | 0 | 0 | 0 |
| $\pi^+$ | $\mathrm{u}\overline{\mathrm{d}}$ | +1 | 0 | 0 |
| $\pi^-$ | $\overline{\mathrm{u}}\mathrm{d}$ | -1 | 0 | 0 |
| $K^0$ | $\mathrm{d}\overline{\mathrm{s}}$ or $\overline{\mathrm{d}}\mathrm{s}$ | 0 | $\mathrm{d}\overline{\mathrm{s}}$ = +1, $\overline{\mathrm{d}}\mathrm{s}$ = -1 | 0 |
| $K^+$ | $\mathrm{u}\overline{\mathrm{s}}$ | +1 | +1 | 0 |
| $K^-$ | $\overline{\mathrm{u}}\mathrm{s}$ | -1 | -1 | 0 |

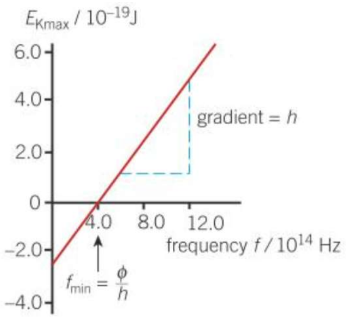
- Neutron decay
  - Decay into proton as neutrons are baryons
  - A down quark changes to an up quark
  - $n \rightarrow p + e^- + \overline{\nu_e}$

## 3.2.1.7 Applications of conservation laws

- Properties conserved in particle interactions
  - Energy and momentum: always
    - Reactants rest energy < products rest energy = reactants KE > products KE
  - Charge: always
  - Baryon number: always
  - Electron lepton number: always
  - Muon lepton number: always
  - Strangeness: only in strong interactions
  - All conservation laws obeyed = the interaction is possible
- β decay
  - $\beta^-$ decay
    - A neutron in a neutron-rich nucleus will decay into a proton
    - A down quark changes to an up quark
    - $n \rightarrow p + e^- + \overline{v_e}$
  - $\beta^+$ decay
    - A proton in a proton-rich nucleus changes into a neutron
    - An up quark changes to a down quark
    - $p \rightarrow n + e^+ + v_e$

# 3.2.2 Electromagnetic radiation and quantum phenomena

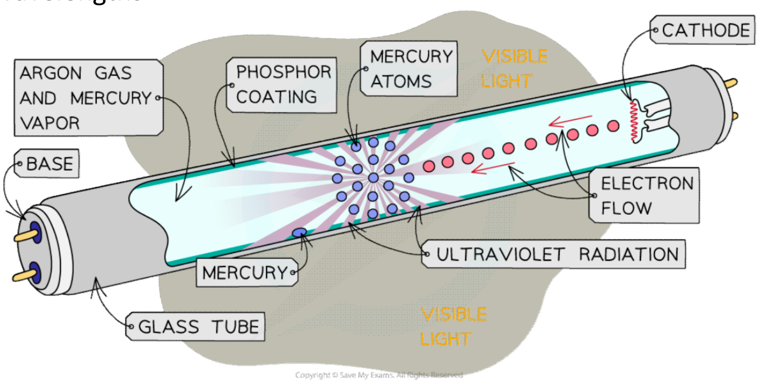
## 3.2.2.1 The photoelectric effect

- The photoelectric effect
    - Photoelectrons are emitted from the surface of a metal after light above a certain frequency (threshold frequency) is shown on it
- Work function
    - The minimum energy to remove an electron from the metal surface when the metal is at **zero potential**
    - Denoted by $\phi$
- Stopping potential ($V_s$)
    - The PD needed to apply across the metal to stop the photoelectrons with the maximum KE ($E_{\mathrm{k(max)}}$)
    - Minimum energy needed to stop photoelectric emissions
    - $E_{k(\max)} = e \times V_s$
- Threshold frequency
    - The minimum frequency of the radiation / light / photon needed to liberate an electron from the surface of a material
    - $hf > \phi$
    - $f_{\min} = \dfrac{\phi}{h}$
- Why wave theory doesn't work
    - There is no photoemission below the threshold frequency even with bright light
        - Wave theory would allow gradual accumulation of energy to cause emission
        - Any frequency of light should be able to cause electron emission
    - Electrons are emitted with no noticeable decay
        - In wave theory time would elapse while an electron gains sufficient energy to leave the surface
    - Intensity of the light does not affect the KE of the emitted electrons
        - High intensity waves would be expected to give higher KE to an electron
- Explanation with the photon model
    - When light is incident on a metal surface an electron at the surface absorbs **a single photon** from the incident light and gains energy equal to $hf$
    - An electron can leave the metal surface if the energy gained > the work function of the metal
    - Excess energy gained becomes KE of the photoelectron
- Effect of increasing the intensity of light
    - There are more photons striking the surface per second
    - Current increases as the number of electrons emitted per second increases
- Photoelectric equation
    - $E = hf = \phi + E_{\mathrm{k(max)}}$
    - $E_{\mathrm{k(max)}} = hf - \phi$
    - Graph
        - 

        - Gradient = $h$
        - y-intercept = $-\phi$
- Energy level of emitted electrons

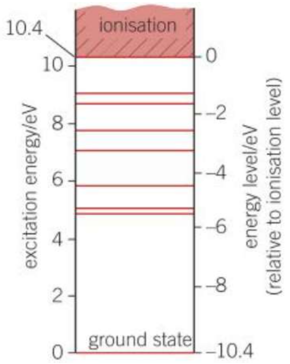
- There exists a maximum value of energy
- Energy of photons are constant ($E = hf$)
- One to one interaction between photon and electron so a fixed amount of KE is transferred
- The energy required to remove an electron varies so the KE of electrons varies
    - Max KE = photon energy - work function
    - Deeper electrons require more energy to remove than $\phi$

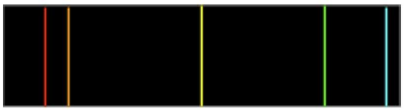
## 3.2.2.2 Collisions of electrons with atoms

- The electron volt
    - The work done when **1 electron** is moved through a **potential difference of 1 V**
    - $\text{work done} = \text{charge} \times \text{potential difference moved through} = qV$
    - **1 eV = 1.6 × $10^{-19}$ J**
- Electron energy level
    - Electrons in atoms can only exist in **discrete energy levels**
    - These electrons can gain energy from collisions with free electrons
    - Excitation
        - Electrons move up in energy level
        - It will quickly return to its original energy level (the ground state) and release energy gained as a photon
    - Ionisation
        - Electrons gain enough energy to be removed from the atom entirely
        - Occurs if **the energy of the free electron is greater than the ionisation energy**
- Excitation energies
    - The energy values at which an atom absorbs energy
- Flourescent tube
    - Filled with mercury vapour
    - High voltage applied which accelerates free electrons through the tube
    - Free electrons collide with the mercury atoms
    - Electrons in the mercury atoms are raised to a higher level
    - The mercury atom become ionised → release more free electrons
    - The new free electrons collide with the mercury atoms, causing them to become excited
    - Mercury atoms de-excites and relaxes to a lower energy level
        - They release photons of energy equal to the energy difference between the levels
        - Frequency is mostly in the **UV range**
    - The fluorescent coating on the inside of the tube absorbs these UV photons and therefore electrons in the atoms of the coating become excited and de-excite releasing photons of **visible light**
    - Emitted radiation consists of (a range of) lower photon energies / frequencies or longer wavelengths
    - 


## 3.2.2.3 Energy levels and photon emission

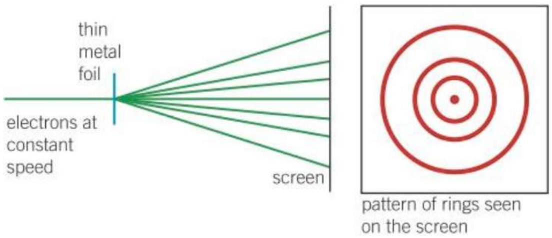
- Ground state
    - When electrons / atoms are in there **lowest energy state** / most stable state
- Excited state
    - **Electron** (in ground state) has moved to higher energy level / shell

- Ionisation energy
  - The minimum energy to remove an electron from an atom from the **ground state**
- Possible energy level of atoms
  - An atom can **only have certain levels** of energy
  - Each allowed energy level = a certain electron configuration of the atom
  - 

- Line spectrum
  - Obtained by passing the light from a fluorescent tube through a diffraction grating or prism
  - Each line = different wavelength of light emitted by the tube = corresponding to the different photon energies emitted
  - Show that electrons in atoms can only transition between discrete energy levels
  - 
- Line absorption spectrum
  - Continuous spectrum with black lines at certain intervals
  - Obtained by passing white light through a cooled gas
  - Black lines represent the possible differences in energy levels
    - The atoms in the gas can only absorb photons of an energy equal to the exact difference between two energy levels
- Why only certain frequencies of light can be absorbed
  - Electrons occupy discrete energy levels
  - They need to absorb an exact amount of energy to move to a higher level
  - Photons need to have certain frequency to provide this energy ($E = hf$)
  - Energy required is the same for a particular atom
  - All energy of the photon is absorbed in **1 to 1** interaction between photon + electron
- De-excitation
  - The electron configuration in an excited atom is unstable due to a vacancy in the shell that the excited electron left
  - The vacancy is filled by an electron from an outer shell transferring to it
- Energy level difference
  - Difference between two energy levels in line spectrum = a specific photon energy emitted by a fluorescent tube / absorbed in a line absorption spectrum
  - Energy of photon emitted = energy lost by the electron = energy lost by the atom
  - Energy of the emitted photon $hf = E_1 - E_2$

### 3.2.2.4 Wave-particle duality

- Evidence for wave-particle duality of light / EM waves
  - Acting as wave: diffraction and interference
  - Acting as particle: photoelectric effect
- De Broglie hypothesis
  - Matter particles have a dual wave-particle nature
- Evidence for de Broglie hypothesis
  - Collisions by incident electrons move electrons in atoms between energy levels
  - Photon emitted when atoms de-excite or electrons move to lower energy levels
  - Wave properties of electrons
    - Electrons can be **diffracted**, shown as concentric rings on scree (also diffraction of

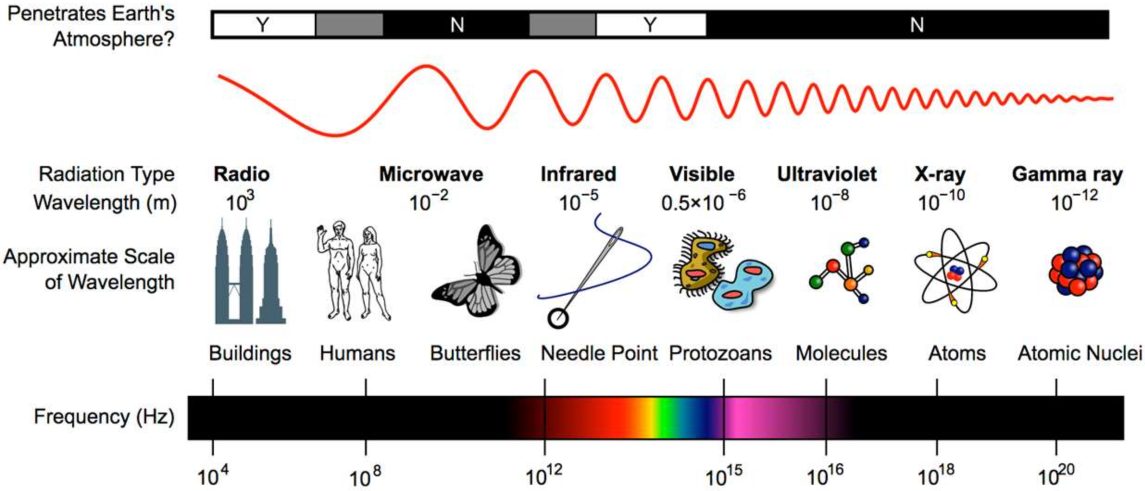
    - electrons by a metal crystal)
    - Foil causes electrons to travel in particular directions
    - Bright rings / maximum intensity occurs where waves **interfere constructively**
    - Particle behaviour would only produce a circle of light as particles scatter randomly
    - **Only waves can experience diffraction** → electrons also have a dual wave-particle nature
- Particle properties of electrons
    - Electrons must provide enough kinetic energy for light to be emitted
    - Instant light as electron can provide the energy in discrete amounts
    - Waves → energy will accumulate gradually so time is needed until light is emitted & light will always be emitted no matter how low the energy is
- Property later also shown for other particles
- 


- De Broglie wavelength
    - The wavelength of the wave-like behaviour of a matter particle
    - $\lambda = \frac{h}{p} = \frac{h}{mv}$
    - Higher particle momentum = shorter wavelength = less diffraction = concentric rings of the interference pattern become closer
- Change in understanding of matter
    - Knowledge and understanding of the nature of matter changes over time in line with new experimental evidence gathered
    - Such changes need to be evaluated through peer review and validated by the scientific community before being accepted

# 3.3.1 Progressive and stationary waves

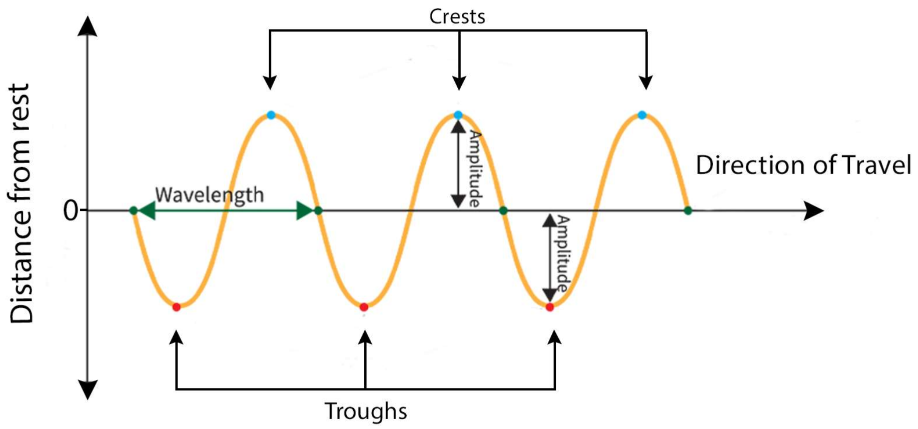
## 3.3.1.1 Progressive waves

- Mechanical waves
  - Involve particles in a substance vibrating
- Electromagnetic waves
  - Travel through space without the need for a substance
  - Electromagnetic spectrum



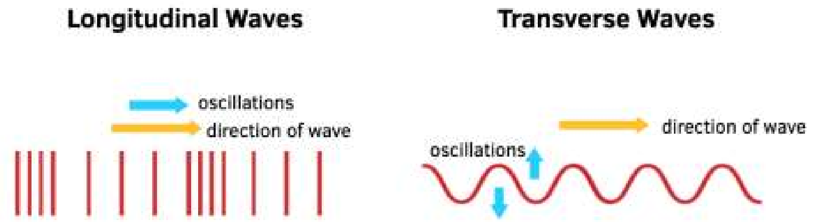

- Progressive wave
  - A wave that transfers energy and momentum from one point to another without transferring the medium itself
  - Made up of particles of an oscillating medium
- Terminologies

| Term | Definition |
|---|---|
| **Displacement** | The vibrating particle's distance and direction from its equilibrium position |
| **Amplitude** | A wave's **maximum displacement** from the equilibrium position (unit = m) |
| **Frequency** $f$ | The number of complete oscillations passing through a point per second (unit = Hz) |
| **Period** $T$ | The time taken to make one oscillation (unit = s) |
| **Wavelength** $\lambda$ | The length of one whole oscillation (e.g. the distance between successive peaks/troughs) (unit = m) |
| **Speed** $c$ | Distance travelled by the wave per unit time (unit = $ms^{-1}$) |
| **Phase** | The fraction of a cycle a vibrating particle has completed since the start of the cycle |
| **Cycle** | One complete cycle of a wave is from maximum displacement to next maximum displacement |

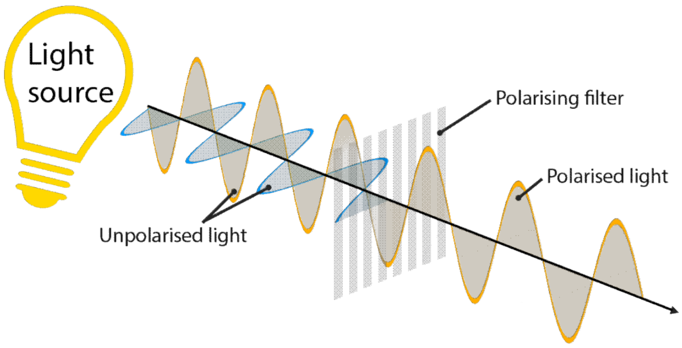
- 

- Phase difference
  - The fraction of a cycle between the vibration of two particles
  - $\text{phase difference in radians} = \frac{2\pi d}{\lambda} = \frac{2\pi \times \text{distance between two points}}{\text{wavelength}}$
- In phase
  - Two points on a wave are in phase if they are both at the same point of the wave cycle
  - Same displacement and velocity
  - Phase difference is a multiple of 360° / 2π
- Completely out of phase / in anti-phase
  - $(2n + 1)\pi$ apart in phase
- Wave speed
  - $c = f\lambda$
- Frequency / period conversion
  - $f = \frac{1}{T}$
  - $T = \frac{1}{f}$
- Properties of waves
  - Reflection
  - Refraction
  - Diffraction

## 3.3.1.2 Longitudinal and transverse waves

- Longitudinal and transverse waves
  - Transverse waves
    - The particles oscillate **perpendicular** to the direction of travel of the wave
    - **Can be polarised**
    - e.g. EM waves, waves on a string
  - Longitudinal waves
    - The particles oscillate **parallel** to the direction of travel of wave
    - The particles get compressed so they have more energy than the particles around them
    - When they vibrate they transfer energy to particles nearby → more compressions
    - **Cannot be polarised**
    - Cannot travel in vacuums (require a medium to propagate)
    - e.g. sound waves
- 

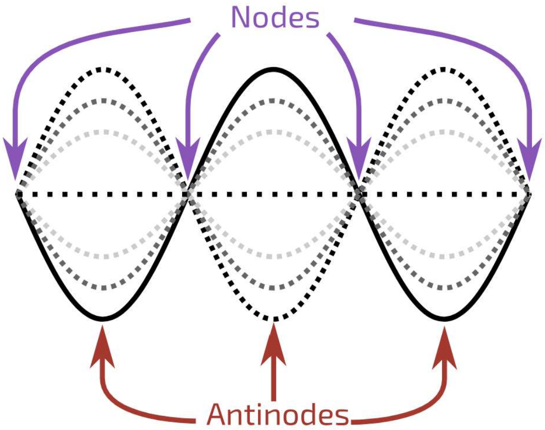
- Types of waves
  - Mechanical waves
    - Oscillations of the particles of the medium

- Electromagnetic waves
    - Oscillating electric and magnetic field that progress through space without the need for a substance
    - Transverse waves
    - All have the same speed in vacuum ($3\times10^{8}$ $ms^{-1}$)
- Polarisation
    - Can only happen when transverse waves travel in one plane only
    - Particle oscillations occur in **only one of the directions** perpendicular to the direction of wave propagation (vibrations stay in 1 plane only)
    - Cannot occur on longitudinal waves as it does not oscillate perpendicular to the direction of travel
    - (Transverse waves are called plane-polarised if the vibrations occur in one plane only, more than one plane = unpolarised)
- Polarising filter
    - 

    - Only the wave along the transmission axis can completely pass through
    - Greater angle between wave + axis = lower light intensity
    - Waves perpendicular to the transmission axis cannot pass through = 0 intensity
- Why only transverse waves can be polarised
    - Transverse waves oscillate perpendicular to direction of travel of wave
        - They initially oscillate in many different planes
        - Intensity is reduced due to oscillations being limited to one plane only
    - Longitudinal waves oscillate parallel to direction of travel of wave
        - There is no perpendicular plane to restrict the oscillations to
- Applications of polarisation
    - Polaroid sunglasses
        - Reduce glare by blocking partially polarised light reflected from water and glass
        - Only oscillations in the plane of the filter is allowed
        - Easier to see
    - EV and radio signals
        - Plane-polarised by the orientation of the rods on the transmitting aerial
        - The receiving aerial must be aligned in the same plane of polarisation to receive the signal at full strength

## 3.3.1.3 Principle of superposition of waves and formation of stationary waves

- The principle of superposition
    - When two or more waves arrive at one point, the resultant displacement is the sum of the displacement of each wave
- Constructive interference
    - Occurs when 2 waves have displacement in the same direction (arrives in phase)
- Destructive interference
    - Occurs when one wave has positive displacement and the other has negative displacement (arrives out of phase)
    - If the waves have equal but opposite displacements (π rad out of phase), total destructive interference occurs (zero amplitude)
- Stationary waves

- Waves where there is no net transfer of energy and momentum from one point to another
- 

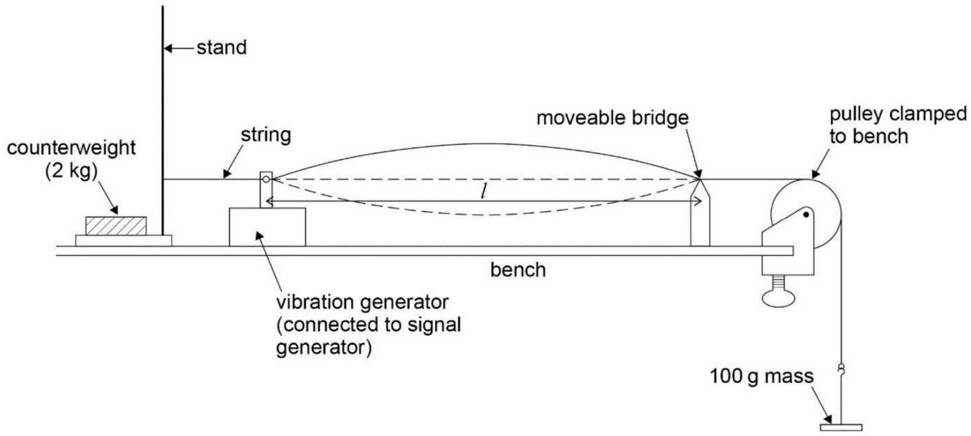

- Formation of stationary waves
  - Formed by the **superposition** of two or more **progressive waves** of the **same frequency and wavelength** and pass through each other in **opposite directions in the same medium**
    - (The waves are emitted by …, **reflected through 180°** by …)
  - Formed as a result of the **superposition** of the progressive waves
  - Amplitudes of the two waves do not need to be the same
  - Constructive interference occurs at where the waves meet in phase so antinodes are formed
  - Destructive interference occurs at where the waves meet completely out of phase so nodes are formed
- Nodes
  - Fixed points in a stationary wave where the amplitude is **minimum** (usually zero)
  - Distance between 2 nodes = $\frac{\text{wavelength}}{2}$
- Antinode
  - Fixed point in a stationary wave pattern where the amplitude is **maximum**
  - The particles have **maximum energy** at the antinode
- Progressive waves + stationary waves comparison
  -

| | **Stationary** | **Progressive** |
|---|---|---|
| **Energy & momentum** | **No net transfer** of energy from one point to another through space | Energy is transferred through space |
| **Wavelength** | Wavelength = 2 × distance between adjacent nodes | Wavelength = distance between 2 particles at the same phase |
| **Frequency** | All particles expect the particles at the nodes vibrate at the same frequency | All particles vibrate at the **same frequency** |
| **Amplitude** | The amplitude varies from **minimum (0) at the nodes to maximum at the antinode**<br>Particles immediately on either side of a node are moving in opposite directions | The amplitude is the **same for each point along wave** |
| **Phase difference between 2 particles (rad)** | Between nodes all particles are **vibrate in phase**<br>$\text{phase difference} = m\pi$<br>$= \text{number of nodes between 2 particles} \times \pi$ | $\text{phase difference} = \frac{2\pi d}{\lambda}$<br>Adjacent points vibrate with different phase |

- Examples of stationary waves
  - Transverse stationary waves
    - String fixed at one end and fixed to a driving oscillator at the other end / plucked
      - Wave reflected at the end of the string
      - Two waves superpose with each other
      - Both ends are fixed so both ends of the string are always nodes
    - Stationary microwaves

        - Reflected on a soft surface
        - The reflected end is an antinode, the emitter end is a node
        - A microwave probe can be used to find the nodes and antinodes
  - Longitudinal stationary waves
    - Sound waves
        - Speaker causes the wave → antinode
        - Open end: when air leaves the tube the pressure around it is lower so it expands → air pushed back to the tube → **antinode**
        - Close end: reflects the wave which reverses its displacement → cancelled out by upcoming wave → **node**
- Harmonics
  - The number of **antinodes** on the string
- First harmonic frequency / fundamental frequency
  - The lowest frequency at which a stationary wave forms
  - Forms a stationary wave with two nodes and a single antinode
  - Distance between adjacent nodes = half a wavelength
  - $\lambda = 2L$
  - $f = \frac{c}{2L} = \frac{1}{2L}\sqrt{\frac{T}{\mu}}$ $(T = \text{tension in the wire}, \mu = \frac{m}{L} = \text{mass per unit length})$
  - $n\text{th harmonic frequency} = n \times \text{first harmonic frequency} = nf_1$
  - nth harmonic frequency = nodes at a distance of $\frac{1}{n}L$
- Factors affecting the fundamental frequency
  - Mass per unit length
  - Tension
  - Length
  - Temperature

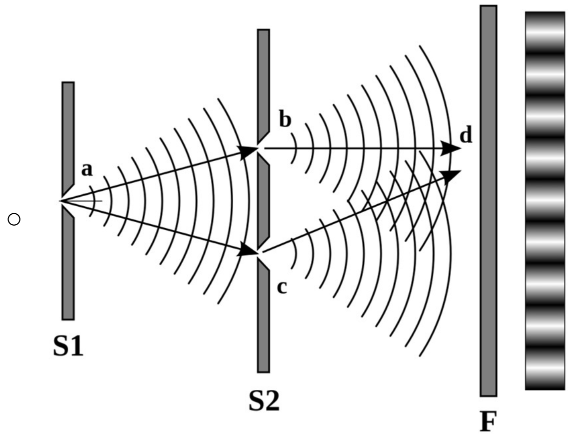
## Required Practical 1 - Stationary Waves

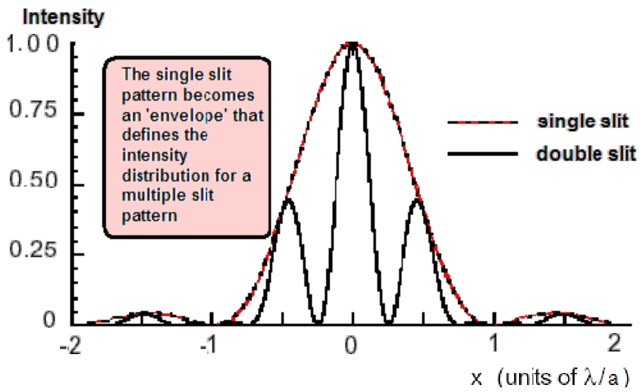
- Frequency vs length / tension / mass per unit length
  - Keep other variables constant
  - Use a signal generator + vibrator connected to signal generator to produce the vibrations
  - Measure length using ruler / tension by hanging mass at one end / mass per unit length by changing the wire
  - Graph of $f$ vs. $\frac{1}{l}$ / $f$ vs $\sqrt{T}$ / $f$ vs $\frac{1}{\sqrt{\mu}}$
  - 

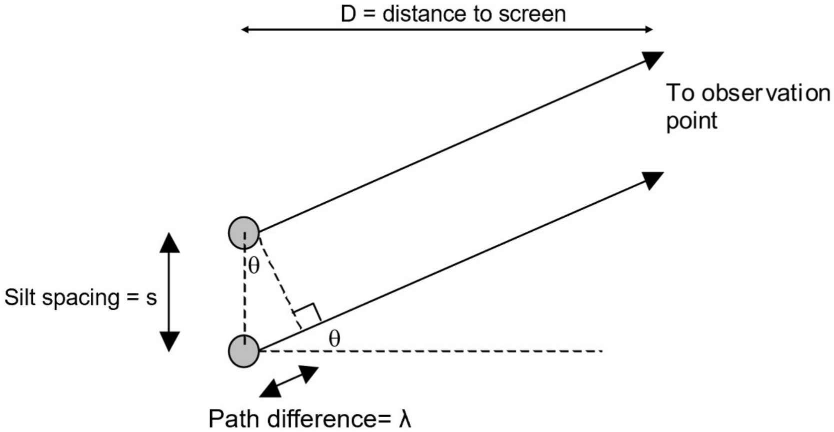
# 3.3.2 Refraction, diffraction and interference

## 3.3.2.1 Interference

- Coherence
    - Waves with a **constant phase difference** and the **same frequency and wavelength**
- Monochromatic
    - Light waves with **a single wavelength only**
- Lasers
    - **Coherent and monochromatic**
    - Usually used as sources of light in diffraction experiments as they form clear interference patterns
- Path difference
    - The difference in the distance travelled by two waves from their sources to where they meet
- Interference of monochromatic light
    - Path difference = $n\lambda$ → constructive interference, gives maximum intensity / reinforcement
    - Path difference = $\left(n+\frac{1}{2}\right)\lambda$ → destructive interference, gives 0 intensity / cancellation
- Interference of longitudinal waves (sound waves)
    - Constructive / reinforcement
        - Compression + compression / rarefaction + rarefaction → greater volume
    - Destructive / cancellation
        - Compression + rarefaction → 0 volume, used for noise cancellation
- Young's double slit experiment
    - Condition for light source
        - Monochromatic → colour filter
        - Coherent → single silt between light source and double silt
        - Laser is both monochromatic + coherent so no colour filter / single slit needed
    - Procedure
        - Shine a coherent light source through 2 slits about the same size as the wavelength laser light so the light diffracts / use 2 coherent sources
        - Each slit acts as a **coherent point source** making a pattern of light and dark fringes
        - Light fringes are formed where the light from both slits meet **in phase** and **interferes constructively** (path difference = $n\lambda$)
        - Dark fringes are formed where the light from both slits meets **completely out of phase** and **interferes destructively** (path difference = $\left(n+\frac{1}{2}\right)\lambda$)



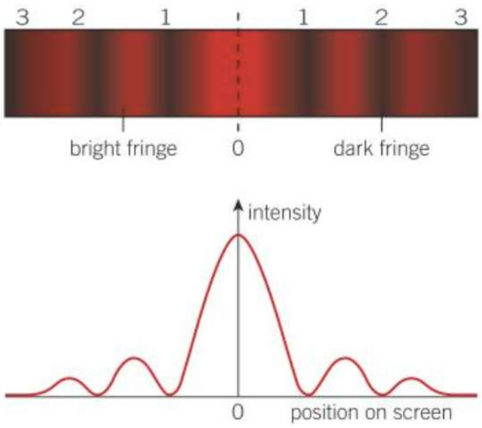
- 

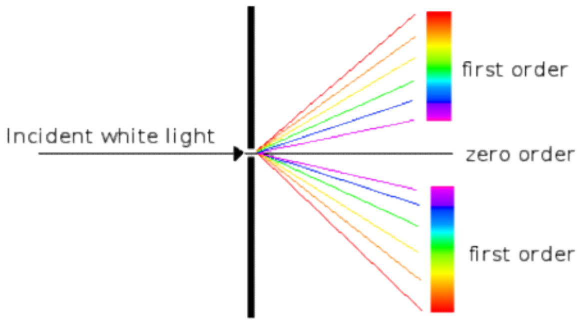

- (Bright) Fringe spacing
  - $w = \frac{\lambda D}{s} = \frac{\text{wavelength} \times \text{distance between slit and screen}}{\text{slit spacing}}$
  - 

  - $\sin\theta = \frac{\lambda}{s}$
  - $\tan\theta = \frac{w}{D}$
  - When $\theta$ is small: $\sin\theta \approx \tan\theta \approx \theta$ so $\frac{\lambda}{s} = \frac{w}{D}$
  - Hence $w = \frac{\lambda D}{s}$
- Significance of Young's double slit experiment
  - **Proved the wave nature of light** since diffraction and interference are wave properties
  - Proved that EM radiation must act as a wave
  - Disproved the theories that light is formed of tiny particles
  - Knowledge and understanding of any scientific concept changes over time in accordance to the experimental evidence gathered by the scientific community
- Interference pattern with white light
  - Wider maxima
  - Less intense diffraction pattern with a central white fringe (all colours are present)
  - Alternating bright fringes which are spectra, violet is the closest to the central maximum and red is the furthest
- Safety precautions with lasers
  - Do not look directly at a laser beam even when it is reflected
  - Wear laser safety goggles
  - Don’t shine the laser at reflective surfaces
  - Display a warning sign
  - Never shine the laser at a person

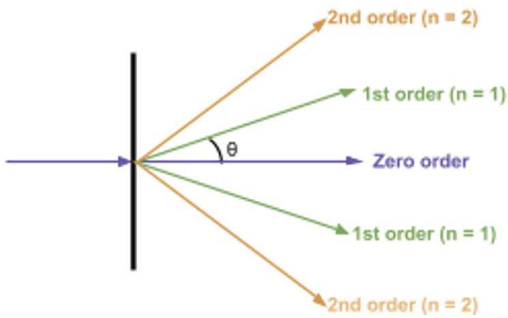
## 3.3.2.2 Diffraction

- Single silt diffraction
  - Monochromatic light
    - Central maximum with highest frequency
    - Decreasing intensity fringes on both sides, equally spaced
    - Central fringe is twice the width of other fringes

- 


- White (non-monochromatic) light
  - White central maxima
  - Fringes on both sides show as spectrums
  - Red furthest, violet closest to the centre
  - 


- Narrower slit = lower intensity for all fringes + wider spacing as waves are more diffracted
- Longer wavelength = more diffracted so wider spacing and fringes

- Fringe spacing for single slit diffraction
  - $w = \frac{D\lambda}{a}$
  - Central fringe = $\frac{2D\lambda}{a}$ wide
- Diffraction grating
  - A slide containing many equally spaced slits very close together
  - When monochromatic light is passed through a diffraction grating the interference pattern is much **sharper and brighter** than it would be after being passed through a double slit
  - Light passing through each slit is diffracted
  - The diffracted light waves from adjacent slits reinforce each other in certain directions only and cancel out in all other directions
  - Distances from the centre where maxima occur $= d \sin\theta = n\lambda$ ($d$ = distance between slits)
    - Angle of diffraction between each transmitted beam and the central beam increases if light of a longer wavelength or a grating with closer slits is used
  - 


- White light incident
  - Spectrum is seen when white light is used
  - Different colours of light have different maxima positions
  - Line absorption spectra and line emission spectra can determine the elements in a substance (photoelectric effect)
- Maximum number of orders visible

        - Use $\theta = 90°$
        - $n_{max} = \left\lfloor \frac{d}{\lambda} \right\rfloor$
- Measuring wavelength of light
    - Diffraction patterns are measured using a spectrometer
        - Angles measured accurate to 1 arc minute ($\frac{1}{60}°$)
    - It can be used to study light from any source and measure wavelengths very accurately
    - Angle measured using a known wavelength → grating spacing calculated
    - Grating can then be used to measure the wavelength of any light
- Applications of diffraction grating
    - Diffraction gratings can be used to observe and measure spectral lines
    - Line emission spectra can be used to identify elements in the vapour gas of the vapour lamp (similar to line absorption spectra)

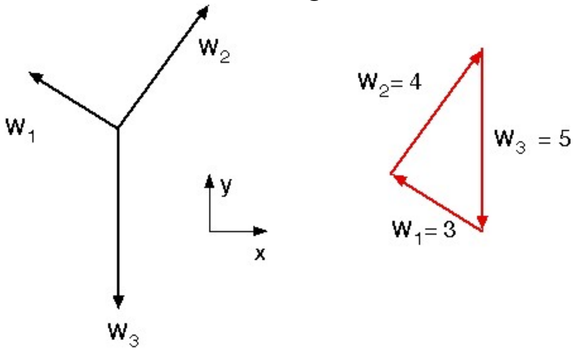
### 3.3.2.3 Refraction at a plane surface

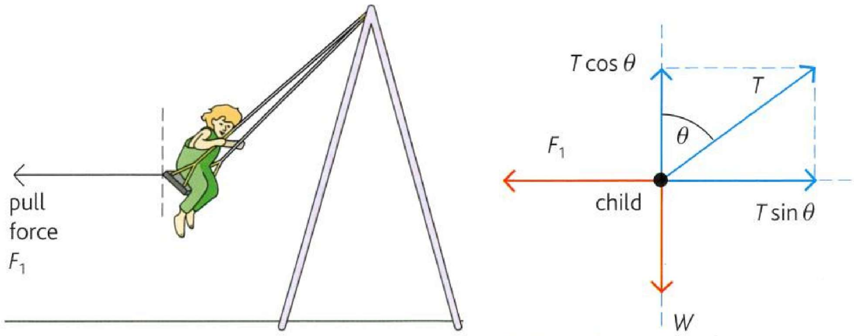
- Refraction
    - Change of direction and **wavelength** when a wave crosses a boundary and its speed changes
- Refractive index of a substance
    - $n = \frac{c}{c_s} = \frac{\sin i}{\sin r}$
    - Refractive index of air ≈ 1
    - Higher refractive index = light travels slower in the substance
- Snell's law
    - $n_1 \sin \theta_1 = n_2 \sin \theta_2$
- Total internal reflection (TIR)
    - For ray going from **more dense** to **less dense** substance & the angle of incidence exceeds the critical angle
    - No refracted light wave since the angle of refraction > 90° so **all the light is reflected**
- Critical angle
    - The angle of incidence at which the angle of refraction is 90°
    - $\sin \theta_c = \frac{n_2}{n_1} (n_2 > n_1)$
- Optical fibre structure
    - Cladding
        - Protects the outer surface of the core from scratching
        - Ensure that no light leaves the core
        - RI of cladding < RI of core
        - Similar RI between cladding and core: larger critical angle → less reflection → less modal dispersion
        - RI of cladding much smaller than core: smaller critical angle → less light escape → more light collected
    - Core
        - The transmission medium for EM waves to progress
- Types of optical fibre
    - Step index fibre
        - The refractive index of each component increases moving from the outside to the centre of the fibre
        - The refractive index within each component is **uniform**
    - Graded index fibre
        - Has a core that has a **gradually decreasing** refractive index
- Pulse broadening
    - The length of a pulse is widened so it may overlap with the next pulse
    - Distorts the information in the final pulse
- Pulse absorption
    - Energy is absorbed by the fibre
    - Amplitude is reduced so information can be lost

- Solution
  - Use more transparent core
  - Use pulse repeaters to regenerate the pulse before significant pulse broadening has taken place
- Material / spectral dispersion
  - Happens if white light is used instead of monochromatic light
  - Light waves interact with the material
  - Red light has the longest wavelength it travels the fastest in the materials
  - Violet light has the shortest wavelength it travels the slowest in the materials
  - Causes pulse broadening
  - Solution
    - Use monochromatic light
- Modal / multipath dispersion
  - Light waves entered at **different angles of incidence** so they are spread out
  - They travel different distances as they take different paths and arrive at the other end at different times
  - Causes pulse broadening
  - Solution
    - Use a narrower core (monomode fibre)
    - Use a cladding with its refractive index as close to the core as possible (larger critical angle → less refraction)
- Applications of optical fibres
  - Endoscopes
  - Transmission of data for communications
- Producing coherent image
  - An incoherent bundle cannot be used to form an image because the ends of the individual fibres are arranged randomly so the image is incorrect
  - In a coherent bundle, the fibres have the same spatial position at each end of the bundle.
  - The light emitted from the end of the bundle is an **exact copy** of the incident light and **a single image** can be reproduced and analysed
  - Coherent bundles are expensive to manufacture so incoherent bundles are used for illumination
- Advantages of optical fibres
  - Less loss of strength
  - No interference
  - Greater bandwidth for more information per second
  - Increased security

# 3.4.1 Force, energy and momentum

## 3.4.1.1 Scalars and vectors

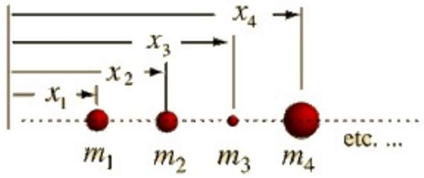
- Vector
  - Any physical quantity that has a direction as well as a magnitude
  - e.g. velocity, force / weight, acceleration, displacement
- Scalar
  - Any physical quantity that is not directional
  - e.g. speed, mass, distance, temperature
- Conditions for equilibrium
  - For an object to be in equilibrium, the sum of all the forces acting on an it must be 0
  - e.g. 3 forces form a closed triangle
    - 

- Explaining what forces balance each other
  - e.g. child on swing
    - Pull force balances with the **horizontal component** of tension
    - Weight balances with the **vertical component** of tension
    - 


a *On a swing* b *Force diagram*

## 3.4.1.2 Moments

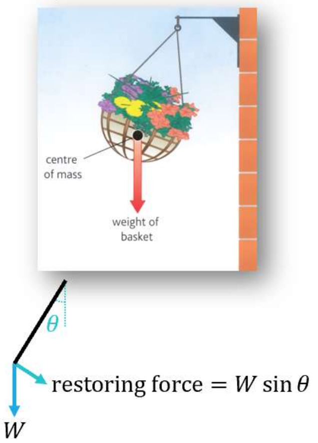
- Moment formula
  - Moment of a force about a point
    $= \text{force} \times \text{perpendicular distance from the pivot point to the line of action of the force}$
- Couple
  - A pair of equal and opposite parallel / coplanar forces acting on a body along different points
  - Exerts a turning force on a body
  - Moment of couple
    $= \text{force} \times \text{perpendicular distance between the lines of action of the forces}$
- Principle of moments
  - For an object in equilibrium, the sum of anticlockwise moments about a pivot is equal to the sum of clockwise moments
- Centre of mass
  - The point at which an object's mass acts
  - The point through which a single force on the body has no turning effect
- Finding centre of mass

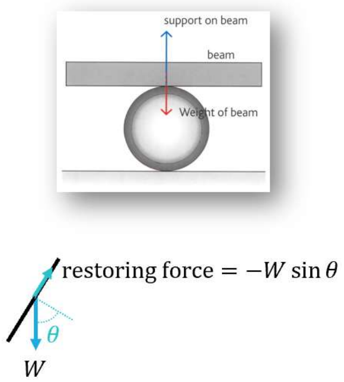
- Uniform regular solid
    - Centre of mass at the centre
- Non-regular card
    - Hang object (and plumb line) by first pivot
    - Draw first line vertically below pivot (by sketching a plumb line hang from the pivot)
    - Hang object (and the plumb line) by second pivot
    - Draw second line vertically below pivot
    - Intersection of lines is the centre of mass
- Multiple mass on a rod
    - $x_{cm} = \dfrac{\sum m_i x_i}{\sum m_i}$
    - 


- Equilibrium stability
    - Stable
        - Object returns to its equilibrium position if displaced (a little)
        - Wide base, low centre of gravity
        - Tilted for a certain angle before centre of mass crosses the pivot point and topple
    - Unstable
        - Object does not return to its equilibrium position if displaced
        - Topple immediately after being tilted
    - Neutral
        - Stay in place when left alone
        - Stay in the new position when moved
        - The object's centre of mass is always exactly over the point which is its 'base'

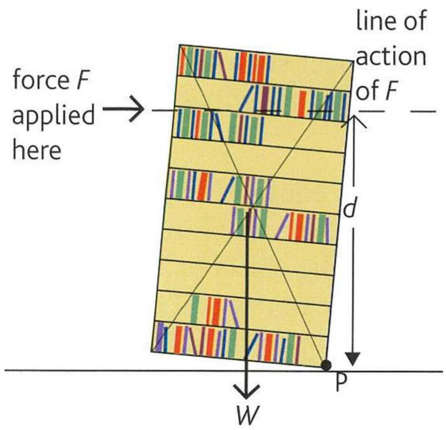
Stable equilibrium

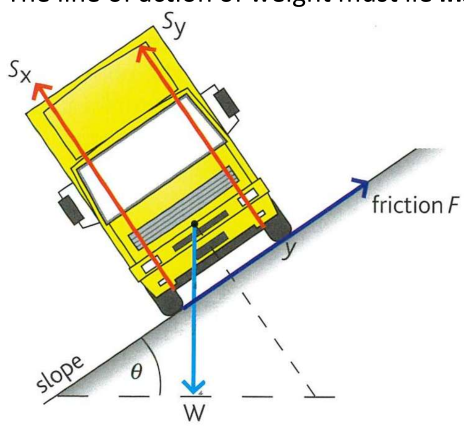
Unstable equilibrium

- 


- Tilting / topping
    - Tilting
        - An object resting on a surface is acted on by a force that raises it up on 1 side
        - For an object to tilt: $Fd > \frac{Wb}{2}$ ($b$ = width of base)

- 

- Toppling
  - Tilted too far
  - Line of action of its weight passes beyond the pivot = topple over if allowed to
- Two support problems
  - When an object is in equilibrium and supported by 2 points then the 2 supports add up to the weight of the object
  - The support closer to the centre of mass provides more of the support force
- On a slope
  - The line of action of weight must lie **inside the base** of the object to prevent tilting
  - 

  - $S_x > S_y$ since $x$ is lower than $y$ (more moment is needed to be produced from $x$ as it is closer to the centre of mass)
- Conditions for equilibrium
  - No resultant force
  - No resultant moment / torque (the principle of moments must apply)

## 3.4.1.3 Motion along a straight line

- Terms

| Term | Definition |
|---|---|
| **Speed** | A scalar quantity describing how quickly an object is travelling |
| **Displacement ($s$)** | The overall distance travelled from the starting position (includes a direction, vector quantity) |
| **Velocity ($v$)** | Rate of change of displacement ($=\frac{\Delta s}{\Delta t}$) |
| **Instantaneous velocity** | The velocity of an object at a specific point in time |
| **Average velocity** | The velocity of an object over a specified time frame |
| **Acceleration ($a$)** | Rate of change of velocity ($=\frac{\Delta v}{\Delta t}$) |
| **Uniform acceleration** | The acceleration of an object is constant |

- SUVAT equations

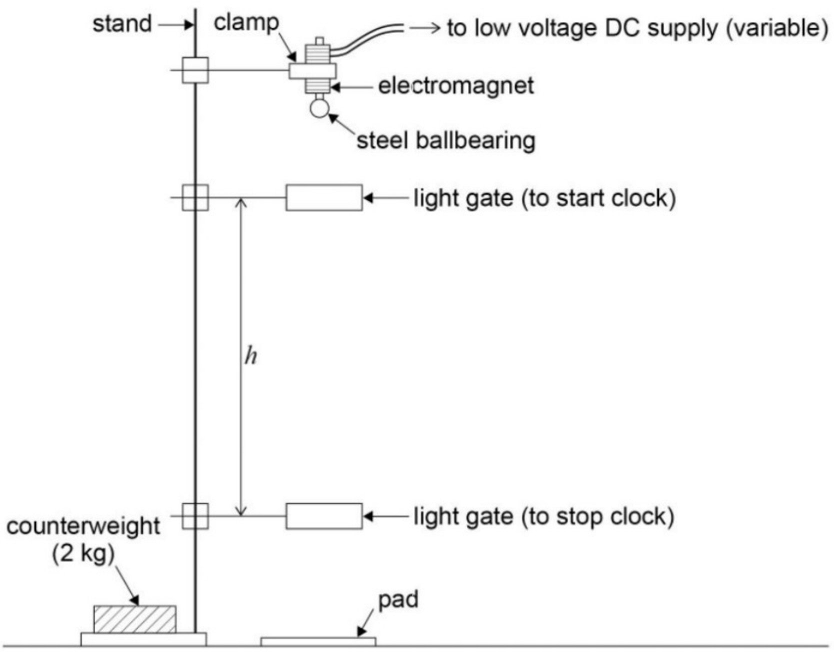
- For uniform acceleration
  - $v = u + at$
  - $s = \left(\frac{u+v}{2}\right)t$
  - $s = ut + \frac{1}{2}at^2$
  - $s = vt - \frac{1}{2}at^2$
  - $v^2 = u^2 + 2as$
- Motion graphs

| | Displacement-time | Velocity-time | Acceleration-time |
|---|---|---|---|
| **Gradient** | Velocity | Acceleration | / |
| **Area** | / | (Change in) displacement | Change in velocity |

- Free fall
  - $u = 0$
  - $a = g$
- Light gate
  - $\text{speed through the light gate} = \frac{\text{length of the object}}{\text{time for the light to be obscured}}$

## Required practical 3 - determining g

- Equipment
  - Stand
  - Bosses and clamps
  - Electromagnet
  - Steel ball bearing
  - Light gate
  - Timer (connected to the light gate)
  - Soft cushion pad
- How to determine $g$ by free fall
  - Set up the apparatus as shown




  - The position of the lower light gate should be adjusted such that the height $h$ is 0.500m, measured using the metre rule
  - Turn on the electromagnet and attach the ball bearing
  - Reset the timer to zero and switch off the electromagnet
  - Read and record the time $t$ on the timer for the ball to pass through the 2 light dates
  - Reduce $h$ by 0.050m by moving the **lower light gate** upwards and repeat this, reducing h by

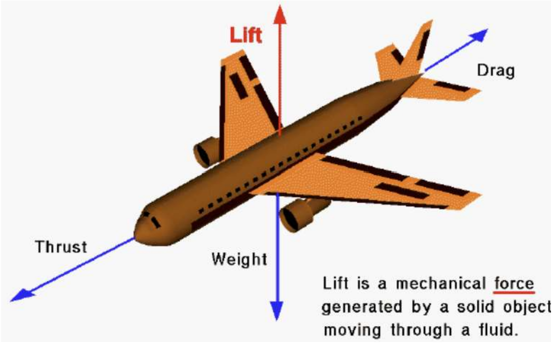
0.050m each time until $h$ reaches 0.250m (at least 5-10 values of $h$)

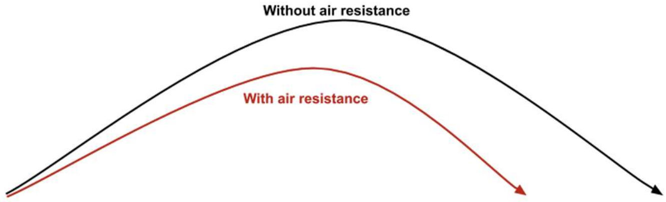
- Repeat the experiment twice more for each value of $h$ and find and record the mean $t$ for each $h$
- Plot a graph of $\frac{2h}{t}$ against $t$ and draw a line of best fit ($\frac{2h}{t} = 2u + gt$)
- Gradient = $g$, y-intercept = $2u$
    - (You might want to draw lines of maximum and minimum gradient and find the mean gradient)

- Errors
    - Systematic
        - Residue magnetism after the electromagnet is switched off may cause t to be recorded as longer than it should be
        - Air resistance reduces the value of $g$ determined
    - Random
        - Large uncertainty in $h$ from using a metre rule with a precision of 1 mm
        - Parallax error from reading $h$
        - The ball may not fall accurately down the centre of each light gate (less time obscuring the light)
        - Random errors are reduced through repeating the experiment for each value of h at least 3-5 times and finding an average time, $t$
- Safety
    - The electromagnetic requires current
        - No water near it
        - Only switch on the current to the electromagnet once everything is set up to avoid electrocution
    - A cushion or a soft surface must be used to catch the ball-bearing so it doesn't roll off / damage the surface
    - The tall clamp stand needs to be attached to a surface with a G clamp so it stays rigid

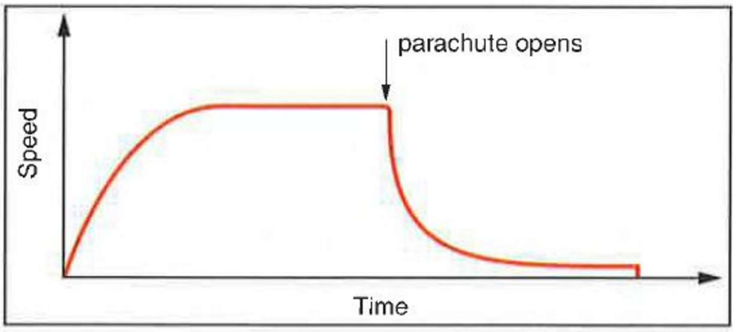
## 3.4.1.4 Projectile motion

- Motion equations ignoring air resistance
    - $v_x = u\cos\theta$
    - $x = ut\cos\theta$
    - $v_y = u\sin\theta - gt$
    - $y = ut\sin\theta - \frac{1}{2}gt^2$
- Range and maximum height
    - $\text{Maximum height} = \frac{u^2\sin^2\theta}{2g}$
    - $\text{Horizontal range} = \frac{u^2\sin 2\theta}{g}$
    - $\text{Time to maximum height} = \frac{u\sin\theta}{g}$
    - $\text{Time back to starting height} = \frac{2u\sin\theta}{g}$
- Friction
    - A force which opposes the motion of an object
    - AKA drag / air resistance
    - Convert KE into other forms of energy such as heat and sound (work done on the surface / fluid)
- Lift
    - An upward force which acts on objects travelling in a fluid
    - Caused by the object creating a change in the direction of the fluid flow
    - Happens if the shape of the projectile causes the air to flow faster over the top of the object than underneath it
        - Pressure of air on the top surface < pressure of the air on the bottom surface
        - Produces a net upward force

- Acts perpendicular to the direction of fluid flow
- 


- Effect of air resistance (friction)
  - Air resistance / drag force acts in the opposite direction of motion of the projectile
  - Increases as the projectile's speed increases
  - Reduces both the horizontal speed of the projectile and its range
  - Has both horizontal and vertical components
  - Reduces the maximum height of the projectile if its initial direction is above the horizontal and makes its descent steeper than its ascent
  - 

- Terminal velocity
  - Occurs where **the frictional forces acting on an object and the driving forces are equal**
  - No resultant force → no acceleration → travels at constant speed / velocity
- Terminal velocity for objects falling
  - Start initially with free fall (uniform acceleration) briefly
    - The only force acting on the object is weight
    - (Other forces are very small and negligible)
  - Speed still increases but acceleration decreases
    - Air resistance increase because speed increase
    - Resultant force gets smaller
  - Eventually the object falls in uniform velocity (reached terminal velocity)
    - Weight balanced exactly by resistive force upwards
    - Resultant force = 0 so there is no acceleration
    - Air resistance is not increasing anymore because speed is not increasing
    - Potential energy of the object is transferred to the internal energy of the fluid by drag forces
  - Effect of parachute
    - Increase air resistance due to larger area perpendicular to direction of travelling
    - Resultant force upwards so deceleration
    - Air resistance falls as speed falls
    - Decelerates until air resistance get as big as speed so the object falls at uniform speed again
  - Graph
    - Gradient should start with gradient **9.81 m $s^{-2}$** not bigger than **9.81 m $s^{-2}$**

- 

    - (Same to other situations moving through a fluid - resistance increase until the maximum speed is reached)
- Factors affecting terminal velocity
    - Higher mass → higher acceleration → higher terminal velocity
    - Higher volume / CSA → more air resistance → less acceleration →' lower terminal velocity

## 3.4.1.5 Newton's laws of motion

- Newton's 1st law of motion
    - If no resultant external force are acting on a body, it will
        - If at rest, remain at rest
        - If moving, keep moving at constant speed in a straight line
- Newton's 2nd law of motion
    - The acceleration of an object is proportional to the resultant force experienced by the object
    - Acceleration is in the same direction as the resultant force
    - $\text{resultant force} = \text{mass} \times \text{acceleration}$
    - $F = ma$
- Newton's 3rd law of motion
    - When two objects interact, they exert **equal and opposite** forces on each other

## 3.4.1.6 Momentum

- Momentum calculation
    - $\text{Momentum} = \text{mass} \times \text{velocity}$
    - $p = mv$
- The principle of conservation of momentum
    - Momentum is always conserved for a system of interacting objects provided that no external resultant force acts on the system
    - Total final momentum = total initial momentum
- Types of collisions
    - Elastic
        - There is no loss of kinetic energy during the collision
        - Both momentum and KE are conserved
        - $m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$
    - Inelastic: only momentum is conserved, some KE is lost
        - Stick together: $m_1u_1 + m_2u_2 = (m_1 + m_2)v_{1+2}$
        - Colliding objects have less KE after the collision than before the collision
- Explosion
    - $m_1v_1 + m_2v_2 = 0$
    - KE of the objects has increased
- Newton's 2nd law of motion with momentum
    - The rate of change of momentum of an object is proportional to the resultant force on it
    - (The resultant force is proportional to the change of momentum per second)
    - $F = \dfrac{\Delta(mv)}{\Delta t}$
- Impulse
    - The change in momentum
    - $\text{Impulse} = F\Delta t = \Delta(mv)$
- Force-time graph

- Area = $F\Delta t$ = change in momentum
- Stopping distances
  - Thinking distance $s_1 = \text{speed} \times \text{reaction time} = ut_0$
  - Braking distance $s_2 = \frac{u^2}{2a}$
  - Stopping distance $= s_1 + s_2 = ut_0 + \frac{u^2}{2a}$
- Contact and impact time
  - $\text{impact time} = \frac{2s}{u+v} = \frac{2 \times \text{distanced moved by cars}}{\text{initial velocity} + \text{final velocity}}$
  - $a = \frac{v-u}{t}$
  - $F = ma = \frac{mv - mu}{t}$
  - (These calculations only need to be applied onto one car)
- Why airbags / seatbelts / etc. work
  - With no seat belt / airbag / etc. the person would not start to change their momentum until they hit the dashboard or windscreen
  - The person comes to stop quickly (short impact time)
    - Large change of momentum in a short time = large resultant force = large injury ($F = \frac{\Delta(mv)}{t}$)
  - With the seatbelt / airbag / etc. they will have a longer impact time (comes to stop more slowly)
    - They will experience a smaller resultant force and so less injury

## 3.4.1.7 Work, energy and power

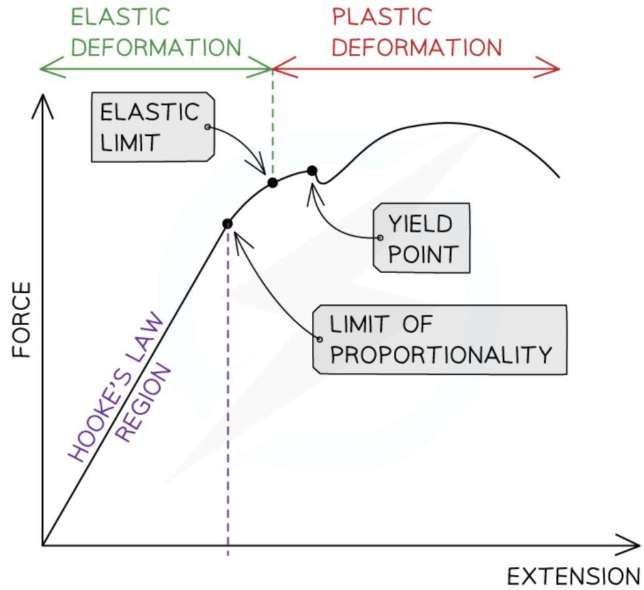
- Work
  - $\text{Work done} = \text{force} \times \text{distance moved in the direction of the force}$
  - Unit = joules (J)
  - $W = Fs\cos\theta = \text{force} \times \text{displacement} \times \text{angle between force and direction of motion}$
- Force-displacement graphs
  - Area under line = work done
- Power
  - Rate of doing work = rate of energy transfer
  - $P = \frac{\Delta E}{\Delta t} = \frac{\Delta \mathrm{W}}{\Delta t} = Fv\cos\theta = \text{driving force} \times \text{velocity} \times \cos\theta$
- Efficiency
  - $\text{Efficiency} = \frac{\text{Useful work done}}{\text{Total energy input}} = \frac{\text{Useful energy output}}{\text{Total energy input}} = \frac{\text{Useful power output}}{\text{Total power input}}$
  - Can be expressed as a percentage

## 3.4.1.8 Conservation of energy

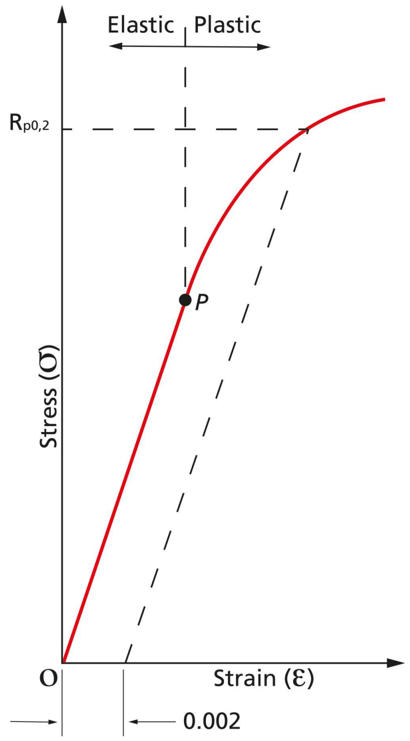
- Principle of conservation of energy
  - Energy cannot be created or destroyed but transferred from one store to another
- Kinetic energy
  - $E_k = \frac{1}{2}mv^2$
- (Gravitational) potential energy
  - $E_p = mg\Delta h$

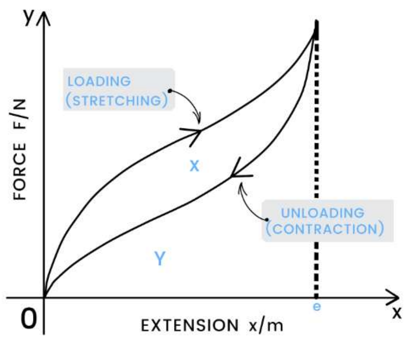
# 3.4.2 Materials

## 3.4.2.1 Bulk properties of solids

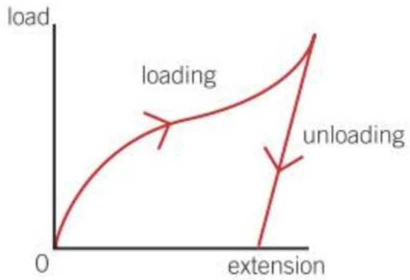
- Density
  - Mass per unit volume
  - $\rho = \dfrac{m}{V}$
- Hooke's law
  - The extension of the material is directly proportional to the load applied up to the limit of proportionality
  - $F = k\Delta L = \text{spring constant (stiffness)} \times \text{extension}$
- Springs combined together
  - Springs in parallel
    - $k = k_1 + k_2 + \cdots + k_n$
  - Springs in series
    - $\dfrac{1}{k} = \dfrac{1}{k_1} + \dfrac{1}{k_2} + \cdots + \dfrac{1}{k_n}$
- Energy transfer in springs
  - Hung vertically and stretched: KE → elastic strain energy
  - Force removed: elastic strain energy → KE → GPE
- Force-extension graph
  - 

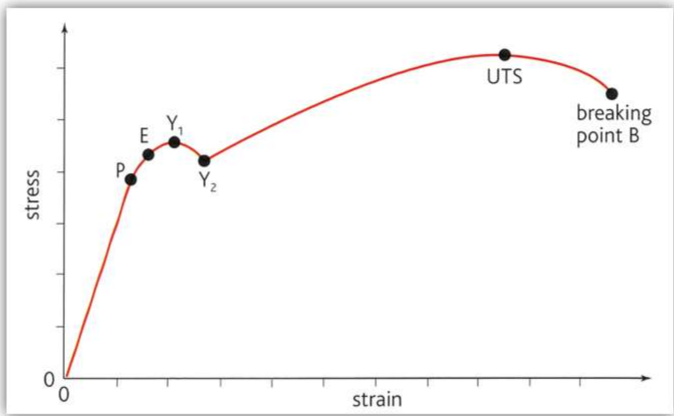
  - Limit of proportionality: the point beyond which Hooke's Law is no longer true
  - Elastic limit: the point beyond which the material will be permanently deformed, right after limit of proportionality
  - Brittle materials: extend very little before it breaks / fractures at a low extension
  - Plastic materials: experience a large amount of extension as the load is increased, especially after the elastic limit
- Types of stretches
  - Elastic
    - Material **returns to original shape** once force is removed
    - All the work done is stored as elastic strain energy
  - Plastic
    - Material **does not return to original shape** once force is removed
    - Work is done to move atoms apart so energy is not stored as elastic strain energy but dissipated as heat
- Types of deformation
  - Tensile deformation
    - Deformation that **stretches** an object

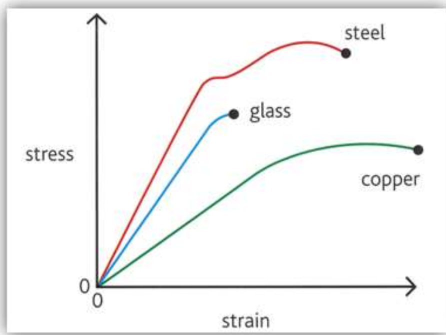
- Compressive deformation
    - Deformation that **compresses** an object
- Strain energy
    - The area under the force-extension graph = work done to stretch the energy = strain energy
- Elastic strain energy in springs
    - $E_p = \frac{1}{2}F\Delta L = \frac{1}{2}k(\Delta L)^2 = \text{area under force-extension graph}$
- Loading & unloading materials
    - **Area between loading and unloading lines = work done to permanently deform the material**
    - Plastic deformation
        - When a material is stretched beyond its elastic limit it will not return to its original length after the load is removed (permanent extension / deformation)
    - Metal wire
        - Loading (the proportional part) + unloading curves are the same straight line
        - Gradient of the unloading line remains the same because the stiffness only changes with material
        - 

    - Extension of elastic materials graph e.g. seatbelts
        - Loading and unloading curves are not linear & not the same
        - During unloading the change in length is greater for a given change in tension
        - Returns to the original length when unloaded
        - 

    - Extension of plastic materials graph
        - The loading curve is not linear
        - During unloading the change in length is greater for a given change in tension
        - Does not return to its original strength

- 


- Stress-strain curves
  - 

  - Before limit of proportionality (P)
    - **Gradient = Young modulus of the material**
    - Tensile stress ∝ tensile strain
    - The material obeys Hooke's law
  - Elastic Limit (E)
    - Up to this point the material returns to its original length when the load acting on it is completely removed
    - Beyond this limit the material doesn't return to its original position and a plastic deformation starts to appear in it
  - Yield point ($Y_1$ and $Y_2$)
    - The stress at which the material starts to deform plastically
    - After the yield point is passed, **plastic deformation occurs**
    - 2 yield points: upper ($Y_1$) + lower yield point ($Y_2$)
      - At the upper yield point the wire weakens temporarily
      - At the lower yield point a small increase in stress causes a large increase in strain and the wire undergoes plastic flow
  - Ultimate tensile stress (UTS)
    - The maximum stress a material can withstand
    - After UTS the wire loses its strength, extends and **becomes narrower at its weakest point**
    - **Plastic deformation stops**
  - Fracture / breaking point (B)
    - The point in the stress-strain curve at which the material breaks / fractures
- Stress / strain curve for different materials
  - 

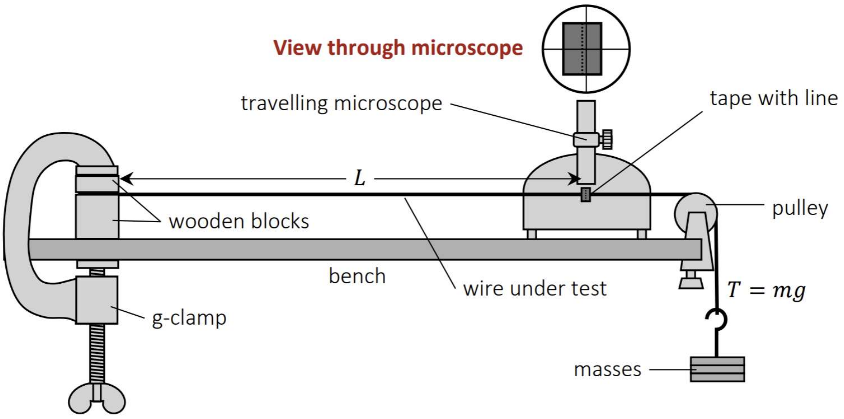
  - Brittle materials (e.g. glass) snap without noticeable yield

- Ductile materials can be drawn into a wire (e.g. copper)

## 3.4.2.2 The Young modulus

- Tensile strain
  - Extension per unit length
  - $\sigma = \dfrac{F}{A}$
- Tensile stress
  - The force per unit cross-sectional area
  - $\varepsilon = \dfrac{\Delta L}{L}$
- Young modulus
  - $E = \dfrac{\text{tensile stress}}{\text{tensile strain}} = \dfrac{FL}{A\Delta L}$
  - Unit = Pascal (Pa)
  - Measures the **stiffness of the material** (higher Young modulus = stiffer material)
  * Young modulus is specific to the material and **doesn't change**
  * Young modulus = gradient of the straight line part of the stress strain graph

## Required practical 4 - determining the Young modulus

- Method
  - Measure the initial length of wire with a ruler
  - Measure the initial diameter of wire with a micrometer
    - Measure in several places and take mean
    - Diameter is very small so it cannot be measured by a ruler but only with a micrometer
  - Mark a cross onto the wire with a tape
  - Align the travelling microscope with the cross
    - Extension can be very small so a microscope is needed
  - Add load and align the travelling microscope with the cross again
  - Read off the extension of the wire
  - Repeat for a range of loads
  - Repeat up to the limit of proportionality / elastic limit
  - Repeat the experiment 2 more times for each value of load and calculate mean extension
  - Calculate tensile stress and strain for each load value
  - Plot a graph of stress against strain
  - Young modulus = gradient of the linear part of the graph
  - 

- Measurements
  - Length of the wire between clamp and mark (metre rule)
  - Diameter of the wire (micrometer, measure several positions + mean taken)
  - Extension of wire for a known mass (by moving travelling microscope and checking the scale)
  - Repeat readings for increasing load

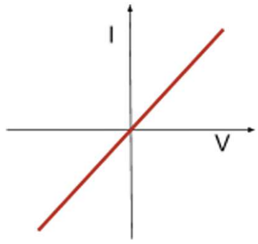
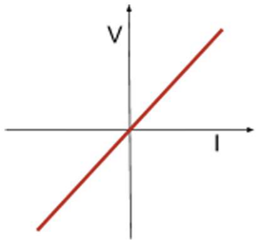
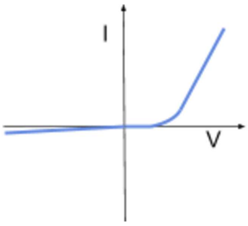
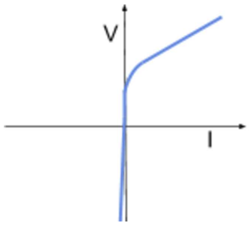
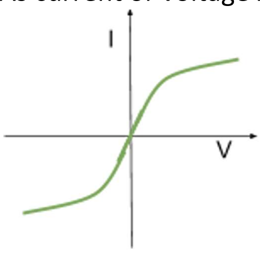
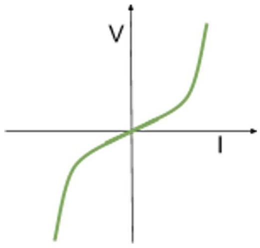
# 3.5.1 Current electricity

## 3.5.1.1 Basics of electricity

- Charge
  - Measured in coulomb (C)
  - ★ Charge of 1 electron = $-1.6 \times 10^{-19}$ C
- Electric current (I)
  - The flow of charge per unit time / the rate of flow of charge
  - $I = \frac{\Delta Q}{\Delta t}$
- Potential difference (V)
  - The energy transferred per unit charge between two points in a circuit
  - When a charge of 1 C passes through a p.d. of 1 V, it does 1 J of work
  - $V = \frac{W}{Q}$
- Resistance (R)
  - A measure of how difficult it is for charge carriers to pass through a component
  - $R = \frac{V}{I}$
- Capacity
  - A measure of the total amount of charge which the battery can push around a circuit
  - Commonly measured in ampere-hours (A h)
  - ★ 1 Ah = a current of 1 A can flow for 1 hour = 3600 C
- Types of charge carriers
  - Insulator
    - Each electron is attached to an atom and cannot move away from the atom
  - Metallic conductor
    - Most electrons are attached to metal ions but some are delocalised
    - Delocalised electrons can carry charge through the metal
    - When a voltage is applied across the metal these conduction electrons are attracted towards the positive terminal of the metal
  - Semiconductor
    - Number of charge carriers increase with an increase of temperature (electrons break free from the atoms of the semiconductor)
    - Resistance fall as temperature rise

## 3.5.1.2 Current-voltage characteristics

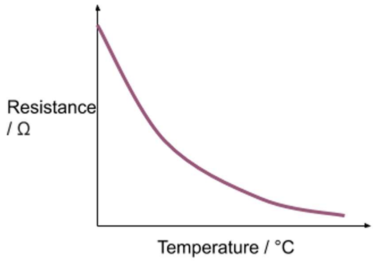
- Ohm's law
  - The current through a conductor is directly proportional to the potential difference across the conductor provided that temperature and other physical conditions remain constant
  - $V = IR$
  - * **Not** the definition of voltage
- Types of different conductors
  - Ohmic conductor
    - Follows Ohm's law
    - Constant resistance as long as temperature and other physical conditions remain constant
    - Current-voltage graph will look like a straight line through the origin

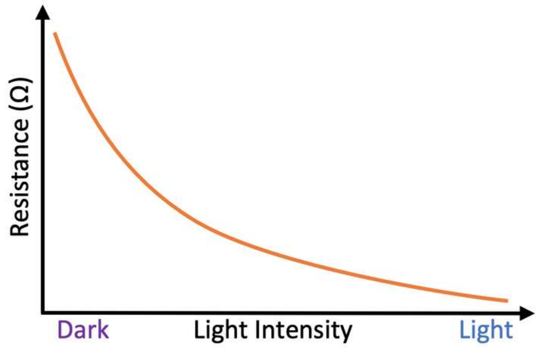
  -  
- Semiconductor diode
  - Only lets current flow in one direction, converts AC to DC
  - Forward biased: allow current to flow easily past the threshold voltage (smallest voltage needed to allow current to flow)
  - Reverse biased: the resistance of the diode is extremely high so that only a very small current can flow
  -  
- Non-ohmic conductors e.g. filament lamp
  - Does not have a constant resistance
  - As voltage increases current increases
  - More electrons flow through the wire per second
  - Higher **rate** of collisions between ions in the lattice structure and electrons
  - Conducting electrons slow down more and lose more kinetic energy so current falls and resistance increases
  - As current or voltage increases resistance increases so the gradient is not constant
  -  

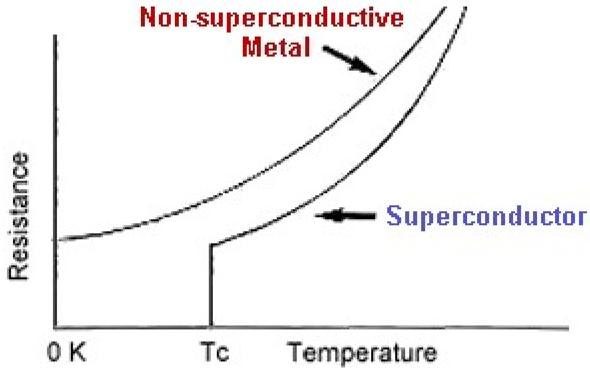
★ • Assumptions
  - Assume ammeters and voltmeters are ideal unless otherwise stated
  - Ammeters can be assumed to have zero resistance
  - Voltmeters can be assumed to have infinite resistance

## 3.5.1.3 Resistivity

- Resistivity ($\rho$)
  - Resistance per unit length × area of cross section
  - $\rho = \frac{RA}{L}$ or $R = \frac{\rho L}{A}$
  - Unit = Ω m
- Effect of temperature on the resistance of metal conductors
  - When the temperature of a metal conductor increases its resistance will increase
  - Metal ions gain KE from heating and vibrate more so they take up more space
  - More collisions between electrons and metal ions **per second** so they slow down more
  - Current falls so resistance increases
- Effect of temperature on the resistance of thermistors
  - When the temperature of a thermistor increases, its resistance will decrease
  - Increasing the temperature of a thermistor causes electrons to be emitted from atoms = more charge carriers = current increase

- 

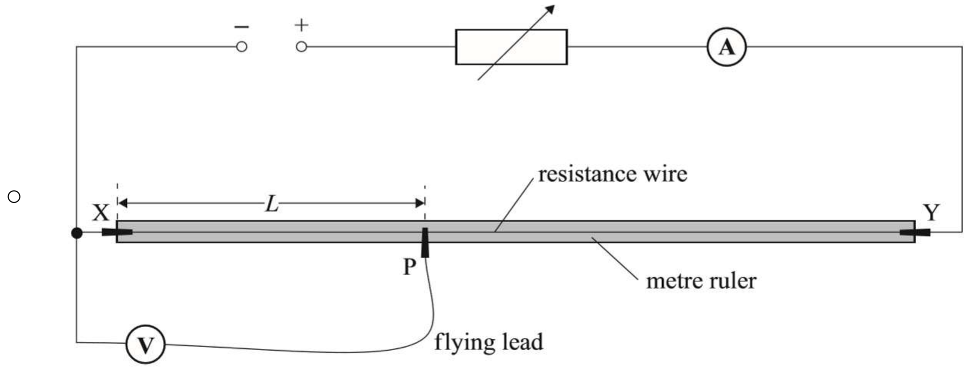

- Application of thermistors
  - Temperature sensors
    - Trigger an event to occur once the temperature drops or reaches a certain value
    - e.g. turn on the heating once room temperature drops below a specific value
- LDR
  - Resistance decreases as light intensity decreases
  - Used to trigger certain events
  - 


- Superconductivity
  - A property of certain materials which have **zero resistivity** at and below a critical temperature ($T_c$) which depends on the material
  - Resistivity decreases with temperature
  - Zero resistivity = zero resistance
  - Critical temperature normally extremely low (close to 0 K)
  - 


- Applications of superconductors
  - Power cables
    - Reduce energy loss due to heating to zero during transmission
  - Production of strong magnetic fields
    - Do not require a constant power source
    - Used in maglev trains / certain medical applications
- Resistance of a wire
  - Normally assumed to be 0 so no PD is lost between 2 points on a wire with no resistors between them
  - The assumption can break down if the current is high / resistance in the rest of the circuit is low

## Required practical 5 - determining wire resistivity

- Method
  - Set up the circuit as shown

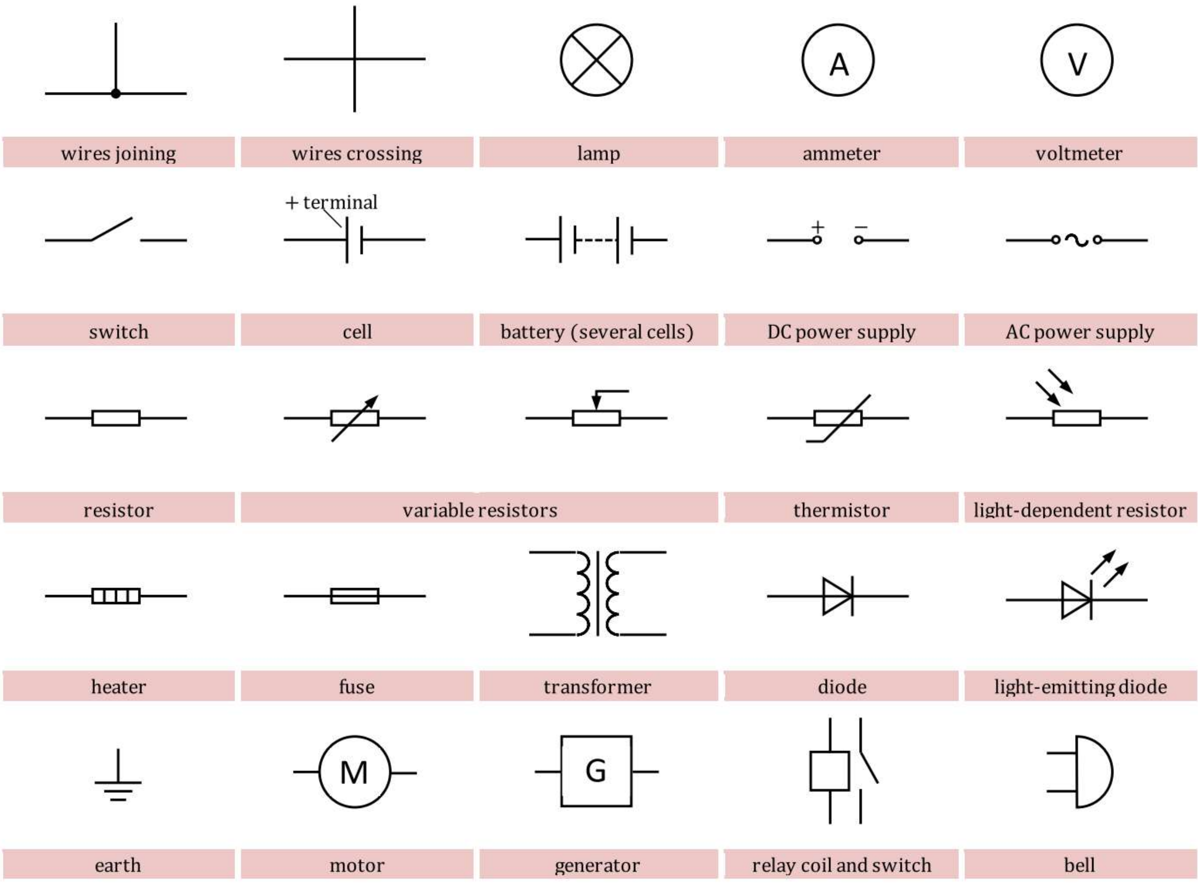


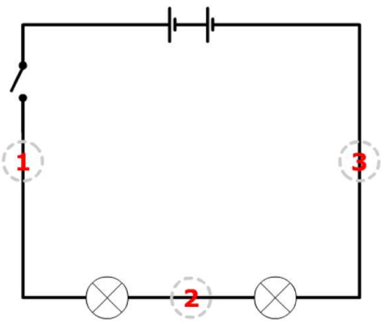

- Connect the flying lead to the wire so that 0.10 m of the wire has its resistance measured
- Switch on the power supply and adjust the voltage of it so that the current in the circuit is 0.50 A
- Turn off the power supply between readings so the wire does not heat up and increase in resistance
- Measure and record the length and voltage across the wire by taking reading on the voltmeter
- Move the flying lead to increase the length by 0.10 m and repeat the measuring process for lengths up to 1.00 m
- Repeat the experiment twice for each reading and calculate an average voltage at each length
- Calculate resistance at each length by $R = \frac{V}{I}$
- Plot a graph of resistance against length
- Resistivity = gradient × cross sectional area (gradient = $\frac{\rho}{A}$)

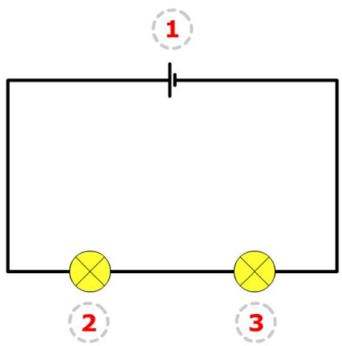
- Errors
  - Random Errors
    - The current flowing through the wire will cause its temperature to increase and increase its resistance and resistivity
      - Only allow small currents to flow through the wire
      - Therefore the temperature is kept constant and low by small currents
      - The current should be switched off between readings so its temperature doesn't change its resistance
    - Make at least 5-10 measurements of the diameter of the wire with the micrometer screw gauge and calculate an average diameter to reduce random errors in the reading
    - The wire should be free from kinks and held straight so the measurement of the length is as accurate as possible.
  - Systematic errors
    - Zero error when measuring wire length
- Safety Considerations
  - When there is a high current, and a thin wire, the wire will become very hot
  - Make sure never to touch the wire directly when the circuit is switched on
  - Switch off the power supply right away if you smell burning
  - Make sure there are no liquids close to the equipment, as this could damage the electrical equipment

## 3.5.1.4 Circuits

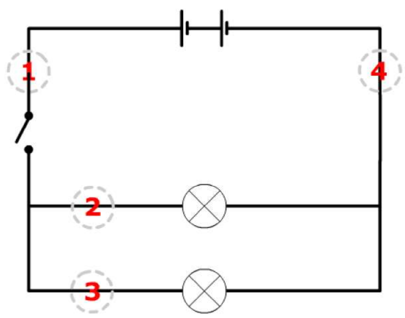
- Circuit symbols

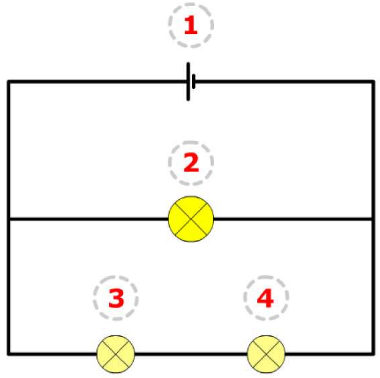
- 


- Series circuit properties
    - The current is the same at all points
        - 

        - ① = ② = ③
    - The sum of potential differences across the components is equal to the total EMF of the power supply
        - 

        - ① = ② + ③
- Parallel circuit properties
    - The current splits up
        - Some of it going one way and the rest going the other
        - Total current in the circuit = sum of the currents in the branches

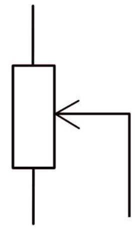
        - 

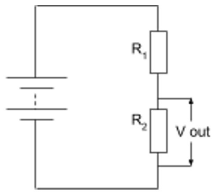
        - ① = ② + ③ = ④
    - Total voltage of a parallel circuit has the same value as the voltage across each branch
        - 

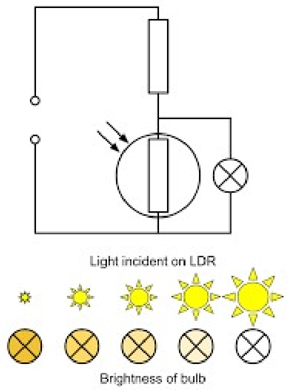
        - ① = ② = ③ + ④
- Total voltage of cells
    - Cells joined in series
        - $V_T = V_1 + V_2 + V_3 + \cdots$
    - Identical cells joined in parallel
        - Total voltage = voltage of one cell as current is split equally between branches so overall pd is the same as if the total current was flowing through a single cell
        - $V_T = V_1 = V_2 = V_3 = \cdots = \varepsilon - \frac{Ir}{n}$ $= \text{emf} - \frac{\text{total current of the circuit} \times \text{internal resistance of each cell}}{\text{number of cells}}$
        - Total internal resistance = calculated in the same way as other parallel circuits
        - Act like one cell but with reduced internal resistance
- Total resistance calculation
    - In series
        - $R_T = R_1 + R_2 + R_3 + \cdots + R_n$
    - In parallel
        - $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots + \frac{1}{R_n}$
- Power ($P$) and energy ($E$)
    - $P = IV = \frac{V^2}{R} = I^2R$
    - $E = Pt = IVt$
- Kirchhoff's laws
    - In **DC circuits**
    - Kirchhoff's first law (conservation of charge)
        - The total current flowing into a junction is equal to the current flowing out of that junction
        - No charge is lost at any point in the circuit
    - Kirchhoff's second law (conservation of energy)
        - The sum of all the voltages in a series circuit is equal to the battery voltage
        - No energy is lost at any point in a circuit

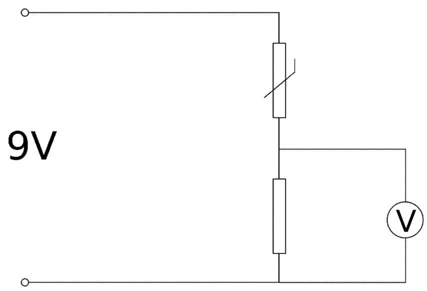
### 3.5.1.5 Potential divider

- Potential divider

- A circuit with several resistors in series connected across a voltage source
- Used to supply constant or variable potential difference from a power supply
- Symbol
    - 

- Using variable resistors
    - Potential divider supply a variable pd
    - Use variable resistor as one of the resistor in series
    - Vary the resistance across = vary pd output
    - 

- Using thermistor / LDR
    - Resistance decreases as temperature / light intensity increases
    - Used to trigger certain events
    - 

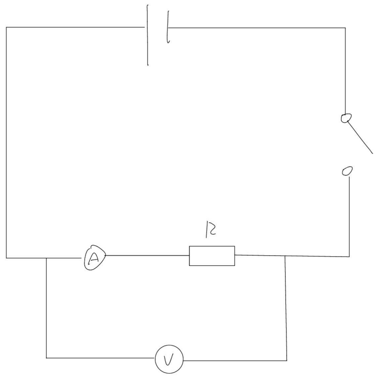



## 3.5.1.6 Electromotive force and internal resistance

- Internal resistance of batteries
    - The resistance of the materials within the battery
    - Caused by electrons colliding with atoms inside the battery so some energy is lost before electrons leave the battery
    - Represented as a small resistor inside the battery
- Terminal pd ($V$)
    - Pd across the resistor(s)
    - $V = \varepsilon - Ir$
- Lost volts ($v$)
    - Pd across the internal resistor in the battery
    - = energy wasted by the cell per coulomb of charge
- Electromotive force
    - The energy converted (from chemical) to electrical energy by a cell for per coulomb of charge that passes through it
    - Can be measured by measuring the voltage across a cell using a voltmeter when there is <u>no current</u> running through the cell
    - $\varepsilon = \frac{E}{Q} = \frac{\text{electrical energy transferred}}{\text{charge}}$
    - $\varepsilon = V + v = I(R + r) = \text{current} \times (\text{load resistance} + \text{internal resistance})$

## Required practical 6 - finding the EMF and internal resistance of a cell

- Method
  - Set up the circuit as shown above with 2 (1.5V) cells connected in series




  - Connect a voltmeter across the resistor to measure the load voltage
  - Close the switch so that the current flows in the circuit
  - Record the ammeter and voltmeter readings
  - Open the switch to cut off the current and prevent heating in the circuit
  - Replace the resistor with a different resistor with a different resistance and repeat the measuring process
  - Use at least 5 different resistors with different resistances
  - Repeat the experiment 2 more times for each resistor and calculate the mean current and voltage
  - Plot a graph of load voltage against current
  - EMF of the cell is the y-intercept of the graph while the internal resistance of the cell is the magnitude of the gradient of the graph
- Safety
  - Another resistor can be included in series with the other to avoid high currents which could be dangerous and make the wires get hot
- Improvements / controls
  - Only close the switch for as long as it takes to read off each pair of readings
    - Prevent the internal resistance of the battery or cell from changing during the experiment due to heating
  - Use fairly new batteries/cells
    - The emf and internal resistance of run down batteries can vary during the experiment