

# A-Levels Physics Notes

By Grass

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## Contents

|           |                                       |           |
|-----------|---------------------------------------|-----------|
| <b>1</b>  | <b>Kinematics</b>                     | <b>1</b>  |
| <b>2</b>  | <b>Dynamics</b>                       | <b>2</b>  |
| <b>3</b>  | <b>Forces</b>                         | <b>4</b>  |
| <b>4</b>  | <b>Work, Energy, and Power</b>        | <b>7</b>  |
| <b>5</b>  | <b>Temperature and Ideal Gases</b>    | <b>8</b>  |
| <b>6</b>  | <b>First Law of Thermodynamics</b>    | <b>10</b> |
| <b>7</b>  | <b>Circular Motion</b>                | <b>12</b> |
| <b>8</b>  | <b>Gravitational Fields</b>           | <b>13</b> |
| <b>9</b>  | <b>Oscillations</b>                   | <b>16</b> |
| <b>10</b> | <b>Wave Motion</b>                    | <b>19</b> |
| <b>11</b> | <b>Superposition</b>                  | <b>21</b> |
| <b>12</b> | <b>Currents of Electricity</b>        | <b>26</b> |
| <b>13</b> | <b>Electric Fields</b>                | <b>30</b> |
| <b>14</b> | <b>D.C. Circuits</b>                  | <b>34</b> |
| <b>15</b> | <b>Electromagnetism</b>               | <b>36</b> |
| <b>16</b> | <b>Electromagnetic Induction</b>      | <b>42</b> |
| <b>17</b> | <b>Alternating Current</b>            | <b>44</b> |
| <b>18</b> | <b>Quantum Physics</b>                | <b>48</b> |
| <b>19</b> | <b>Nuclear Physics</b>                | <b>59</b> |
| <b>20</b> | <b>Practical</b>                      | <b>63</b> |
| 20.1      | Measurements & Calculations . . . . . | 63        |
| 20.2      | Graphing . . . . .                    | 64        |
| 20.3      | Questions post-graphing . . . . .     | 65        |
| 20.4      | Planning questions . . . . .          | 67        |
| <b>21</b> | <b>Bibliography</b>                   | <b>68</b> |

# Kinematics



**Figure 1.1:** [1] Parabolic path travelled by balls thrown at varying angles.

- *Distance* is defined as the total length of *path* travelled.
- *Displacement* is defined as the distance of a point from some reference point *in a specified direction*.
- *Velocity* is defined as the rate of change of displacement.
- *Acceleration* is defined as the rate of change of velocity.
- Four key formulas for kinematics. When the acceleration  $a$  is constant:
  1.  $v = u + at$ ,
  2.  $s = ut + \frac{1}{2}at^2$ ,
  3.  $s = \frac{1}{2}(u + v)t$ ,
  4.  $v^2 = u^2 + 2as$ .

# Dynamics

- *Newton's First Law of Motion* states that an object at rest will remain at rest and an object in motion will remain in motion at constant velocity in a straight line in the absence of an *external* resultant force.
- The *linear momentum* of a body is the product of its mass and velocity. The linear momentum is in the *same direction* as its velocity.
- *Newton's Second Law of Motion* states that the rate of change of momentum of a body is directly proportional to the resultant force acting on the body and occurs *in the direction* of the resultant force.
- *Newton's Third Law of Motion* states that if body A exerts a force on body B, then body B exerts a force of the *same type* that is equal in magnitude and opposite in direction on body A.
- *Impulse* is defined as the product of *average* force acting on an object and the time for which the force acts.
- The *Principle of Conservation of Linear Momentum* states that the total momentum of a system remains constant provided no *external* resultant force acts on the system. i.e.

$$m_1 u_1 + m_2 u_2 = m_1 v_1 + m_2 v_2.$$

- An elastic collision is one where kinetic energy is conserved. i.e.

$$m_1 u_1^2 + m_2 u_2^2 = m_1 v_1^2 + m_2 v_2^2.$$

- The below table provides a quick shortcut, that is particularly helpful in solving multiple choice questions fast. We assume a mass  $m_1$  is moving with velocity  $u$  towards a *stationary* ( $u_2 = 0$ ) mass  $m_2$ .

| Case          | $v_1$        | $v_2$        |
|---------------|--------------|--------------|
| $m_1 = m_2$   | 0            | $u$          |
| $m_1 \ll m_2$ | $\approx -u$ | $\approx 0$  |
| $m_1 \gg m_2$ | $\approx u$  | $\approx 2u$ |

**Table 2.1:** Special cases of elastic collisions.

- For an elastic collision, the relative velocity of approach is equal to the relative velocity after collision:

$$u_1 - u_2 = v_2 - v_1.$$

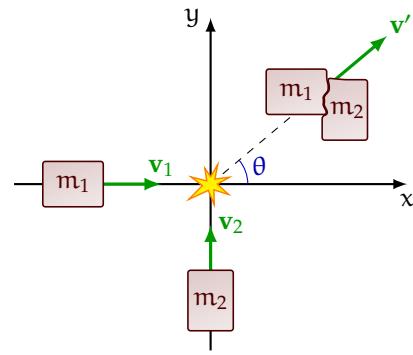
*Note.* The formula is *not*  $u_1 - u_2 = v_1 - v_2$ .

- An inelastic collision is one where kinetic energy is not conserved.
- In a perfectly inelastic collision, the masses coalesce (become one) and move off with the same velocity. In other words,

$$m_1 u_1 + m_2 u_2 = (m_1 + m_2)v.$$



**Figure 2.1:** [2] An illustration of (perfectly) elastic and inelastic collisions.



**Figure 2.2:** [2] Another illustration of a (perfectly) inelastic collision.

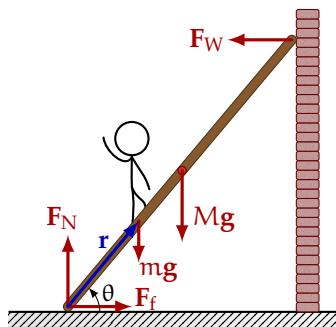
- An explosion does not conserve kinetic energy. But momentum is still conserved. Suppose a (stationary) mass splits into  $n$  masses  $m_1, m_2, \dots, m_n$ . Then we have

$$m_1 v_1 + m_2 v_2 + \dots + m_n v_n = 0.$$

# Forces



**Figure 3.1:** [3] Forces acting on a crane.



**Figure 3.2:** [4] The free body diagram for a ladder, on which a person stands, and which is leaning against a wall.

- Hooke's Law states that the force is directly proportional to the extension in a material if its limit of proportionality is not exceeded.
- The center of gravity of an object is the point at which the entire weight of a body may be considered to act.
- For a mass placed on a ramp, the forces it experiences are as shown below.

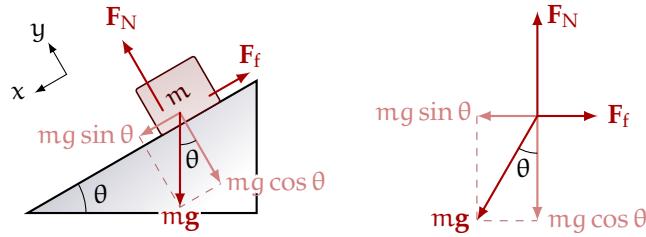


Figure 3.3: [5] Mass  $m$  placed on a ramp whose top surface makes an angle  $\theta$  with the horizontal.

- The *moment* of a force is equal to the product of the force and the *perpendicular* distance of the *line of action* of the force from the pivot. It is also the turning effect of a force.
- Torque of a couple* is defined as the product of one of the forces and the *perpendicular* distance between the *lines of action* of the forces.



Figure 3.4: [6] The torque of a force acting on a wheel

- The *Principle of Moments* states that if a body is in equilibrium, the sum of all the clockwise moments about *any axis* must be equal to the sum of anticlockwise moments about the *same axis*.

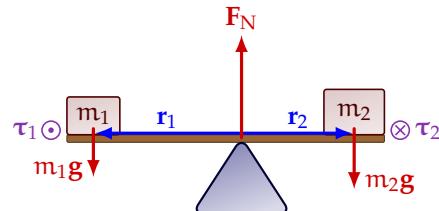


Figure 3.5: [6] The free body diagram of a lever, which is in equilibrium iff  $m_1 g r_1 = m_2 g r_2$ .

- Density* is defined as the mass per unit volume of a substance.
- Pressure* is defined as force per unit area, where the force is *acting perpendicularly* to the area.

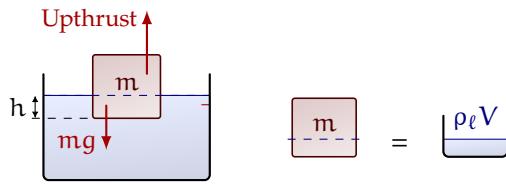


- Deriving  $p = \rho gh$ :

1. Consider a point at a depth  $h$  below the surface of a liquid of density  $\rho$ .
2. The force  $F$  acting perpendicularly on a surface area  $A$  at depth  $h$  is due to the weight of the liquid column above  $A$  to give pressure  $p$ . Thus,  $p = \frac{F}{A} = \frac{mg}{A} = \frac{\rho A h}{g} = \rho gh$ .

**Figure 3.6:** [7] A column of fluid.

- *Upthrust* is the upward force exerted by a fluid on a body immersed in the fluid (due to pressure difference in the fluid).
- *The origin of upthrust:* Upthrust is a result of the pressure difference between top and bottom surfaces of the body, resulting in a net upwards force being exerted on the body by the third medium in which the body is located.



**Figure 3.7:** [8] An illustration of Archimedes' Principle.

- *Archimedes' Principle* states that when a body is totally or partially immersed in a fluid, it experiences an upward force (upthrust) equal to the weight of fluid displaced.
- *The Principle of Floatation* states that, for any object floating in equilibrium, the upthrust is equal to the weight of the object.

- Remember to account for atmospheric pressure, where necessary.
- Suppose a body is subjected to forces acting at three points. Then, for it to be in equilibrium, the lines of action must be *concurrent* (intersection at a common point) or *parallel*.

# Work, Energy, and Power

- *Work done* is defined as the product of a force and the displacement in the direction of the force.
- *One joule of work* is defined as the work done by a force of 1 Newton when its *point of application* moves through a distance of 1 metre in the direction of the force.
- *Energy* is defined as the ability to do work.
- *The Principle of Conservation of Energy* states that energy can neither be created or destroyed in *any process*. It can be transformed from one form to another, and transferred from one body to another.
- Deriving  $E_k = \frac{1}{2}mv^2$ :
  1. Consider a constant horizontal applied force  $F$  acting on an object of mass  $m$  travelling with initial velocity  $u$  to reach a final velocity  $v$  over a displacement  $s$ .
  2. For uniform acceleration,  $v^2 = u^2 + 2as$  so  $as = \frac{1}{2}(v^2 - u^2)$ . Combined with Newton's Second Law,  $W = Fs = mas = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$ . When the object starts from rest,  $u = 0$ .
  3. By conservation of energy, *the work done by force F must be converted into the kinetic energy  $E_k$  of the object*. Hence,  $E_k = W = \frac{1}{2}mv^2 - \frac{1}{2}m(0)^2 = \frac{1}{2}mv^2$ .
- The *Work-Energy Theorem* states that the net work done by *external forces* acting on a particle is equal to the change in kinetic energy of the particle.
- Deriving  $E_p = mgh$ :
  1. Consider an object from the Earth's surface — which is taken as the reference for zero gravitational potential energy — raised up by a *constant force F equal to and opposite to the weight mg* of the object such that the object moves up at *constant velocity* to a height  $h$ .
  2. Thus, the object moves at constant speed so  $\Delta E_k = 0$ . Therefore,

$$\begin{aligned}\Delta E_p &= W \\ E_p - 0 &= Fs \\ E_p &= mgh.\end{aligned}$$

Where  $E_p$  is the gravitational potential energy at height  $h$  above the Earth's surface.

- Know how to  $\Delta E_p = \frac{1}{2}kx^2$  from area under graph.
- *Power* is defined as the rate of doing work.
- Derive  $P = Fv$ :  $P = \frac{dW}{dt} = \frac{Fds}{dt} = Fv$ .

# Temperature and Ideal Gases

- From empirical results, we know that there appears to be a *linear* trend, wherein pressure and volume decrease, when temperature decreases. So, there must be a temperature where pressure is zero, and a temperature where volume is zero. Empirical data shows that the temperature at which this occurs is the same for all gases under all experimental conditions. This temperature is known as *absolute zero*.
- The *Zeroth Law of Thermodynamics* If bodies A and B are separately in thermal equilibrium with body C, then bodies A and B are in thermal equilibrium with each other.
- One mole* is defined as the amount of substance that contains as many elementary particles as there are atoms in 0.012kg of carbon-12.
- Avogadro's Constant*  $N_A$  is the number of atoms in 0.012kg of carbon-12.
- Celsius-Kelvin conversion:  $T \text{ } ^\circ\text{C} = (T + 273.15) \text{ K}$ .

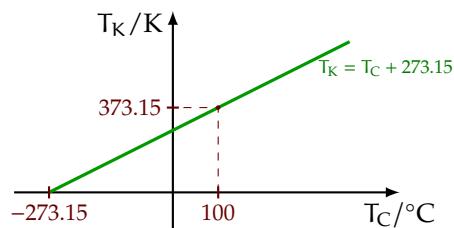


Figure 5.1: [9] Kelvin against celsius graph.

- There is no ideal gas in nature, but at *low pressures* and *high temperatures*, real gases behave like ideal gases.
- Boyle's Law*. When the temperature of an ideal gas remains constant, the product of its pressure  $p$  and volume  $V$  is constant. i.e.  $p_1 V_1 = p_2 V_2$ .
- Charles' Law*. When the pressure of an ideal gas remains constant, its volume  $V$  is directly proportional to its thermodynamic temperature  $T/\text{K}$ . i.e.  $V_1/T_1 = V_2/T_2$ .
- Gay-Lussac's Law*. When the volume of an ideal gas remains constant, its pressure  $p$  is directly proportional to its thermodynamic temperature  $T/\text{K}$ . i.e.  $p_1/T_1 = p_2/T_2$ .
- Let  $n$  be the amount of gas in moles and the integer  $N$  be the number of gas molecules. Then, for the molar gas constant  $R = 8.31 \text{ J K}^{-1} \text{ mol}^{-1}$  and Boltzmann's constant  $k = 1.38 \cdot 10^{-23} \text{ J K}^{-1}$ , the equation of state for an ideal gas is  $pV = nRT = NkT$ .
- Some useful conversions:  $n = \frac{M/\text{kg}}{M/\text{mol}} = \frac{N}{N_A}$ .

|          |  |
|----------|--|
|          | Assumptions of the Kinetic Theory of Gases   |
| <b>M</b> | The molecules of the gas are in <i>rapid</i> and <i>random</i> motion.   |
| <b>A</b> | There are <i>no intermolecular</i> attractive forces.  |
| <b>N</b> | Any gas consists of a <i>very large number</i> of molecules.   |
| <b>T</b> | The duration of collisions is negligible compared to the time interval between collisions.                             |
| <b>E</b> | The collisions between gas molecules, and between gas molecules and the container walls are <i>perfectly elastic</i> . |
| <b>V</b> | The volume of the gas molecules themselves is negligible compared to the volume of the container.                      |

- Real gases are approximately ideal at high temperatures and low pressures.
- Deriving  $p = \frac{1}{3} \frac{Nm}{V} \langle c^2 \rangle$  for an ideal gas:
  - Consider a cubic container of side  $l$  containing  $N$  molecules, each of mass  $m$ .
  - Change in momentum due to *elastic* collision between wall and molecule  $= 2mc_x$ .
  - Time interval between collisions,  $\Delta t = \frac{2l}{c_x}$ .
  - By Newton's 2nd Law,  $F = \frac{2mc_x}{\frac{2l}{c_x}} = \frac{mc_x^2}{l}$ .
  - Since  $A = l^2$ , Pressure due to 1 particle,  $p = \frac{mc_x^2}{l^3} = \frac{mc_x^2}{V}$ .
  - Pressure due to  $N$  particles,  $p_N = \frac{Nmc_x^2}{V}$ .
  - By Pythagoras' Theorem,  $c^2 = c_x^2 + c_y^2 + c_z^2$ . The average speed in the  $x$ ,  $y$ , and  $z$  directions can be taken to be  $c_x = c_y = c_z$  so  $c^2 = 3c_x^2$ . Now,  $p_N = \frac{Nm\langle \frac{1}{3}c^2 \rangle}{V} = \frac{1}{3} \frac{Nm\langle c^2 \rangle}{V}$ .
- The mean translational kinetic energy of an ideal gas molecule molecule is  $\frac{1}{2}m\langle c^2 \rangle = \frac{3}{2}kT$ .
- The total translational kinetic energy of  $N$  ideal gas molecules is  $\frac{3}{2}NkT = \frac{3}{2}nRT = \frac{3}{2}pV$ . This is valid for monoatomic gases.

# First Law of Thermodynamics

- The *heat capacity* of a body is defined as the amount of thermal energy required to raise its temperature by one Kelvin / degree Celsius.
- The specific *heat capacity* of a body is defined as the amount of thermal energy required to raise the temperature of one unit mass of the substance by one Kelvin / degree Celsius.
- The *specific latent heat* of a body is defined as the thermal energy required to change *phase* of one unit mass of a substance, *without a change in temperature*.
- Internal energy* of a system is a sum of *random distribution* of kinetic and potential energy associated with the molecules of the system.
- An ideal monoatomic gas of N atoms only has translational motion and no intermolecular potential energy,  $U = E_k = N \cdot \text{translational } E_k$  of one atom =  $\frac{3}{2}NkT$ .
- For non-monoatomic ideal gases,  $U \neq \frac{3}{2}NkT$ . But we know that  $U_{\text{Total}} \propto NT$  and  $U_{\text{one molecule}} \propto T$ .
- The *First Law of Thermodynamics* states that the *increase* in internal energy of a closed system is the *sum* of heat *supplied* to the system and the work done *on* the system. i.e.  $\Delta U = Q + W$ .
- The work done  $W$  on a gas against a constant external pressure  $p$  is such that  $W = -p\Delta V$ .
- In general, the work done on a gas is  $W = - \int_{V_i}^{V_f} p \, dV$ .
- An *isothermal process* is one that takes place without a change in temperature, i.e.  $\Delta T = 0$ . Thus, for an ideal gas,  $\Delta U = \frac{3}{2}Nk\Delta T = 0$ .
- An *iso-volumetric/isochoric process* is one that takes place without a change in volume, i.e.  $\Delta V = 0$ . Hence, when the external pressure is constant,  $W = 0$ .
- An *isobaric process* is one that takes place without a change in pressure, i.e.  $\Delta p = 0$ .
- An *adiabatic process* is one that takes place without heat transfer, i.e.  $Q = 0$ . Therefore,  $Q = 0$ .

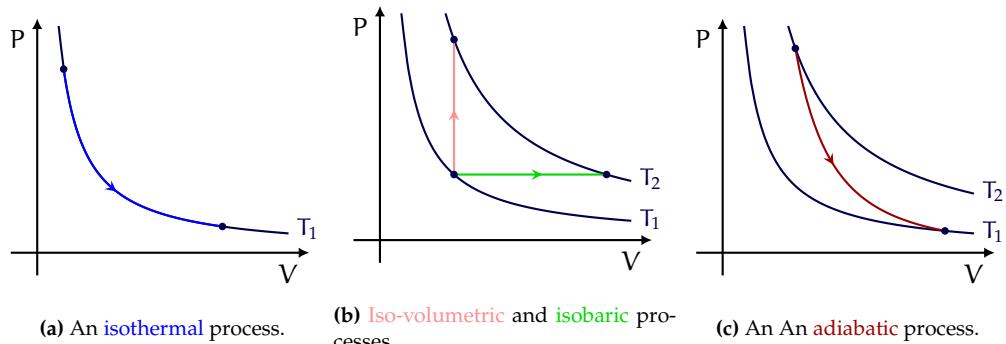


Figure 6.1: [10] Illustrations for isothermal, iso-volumetric/isochoric, isobaric, and adiabatic processes.

- A thermodynamic cyclic process is one that eventually returns to its initial state.
  - $\Delta U = 0$  so  $Q = -W$ .
  - The net work done by/on the gas is given by the area enclosed by the closed loop.

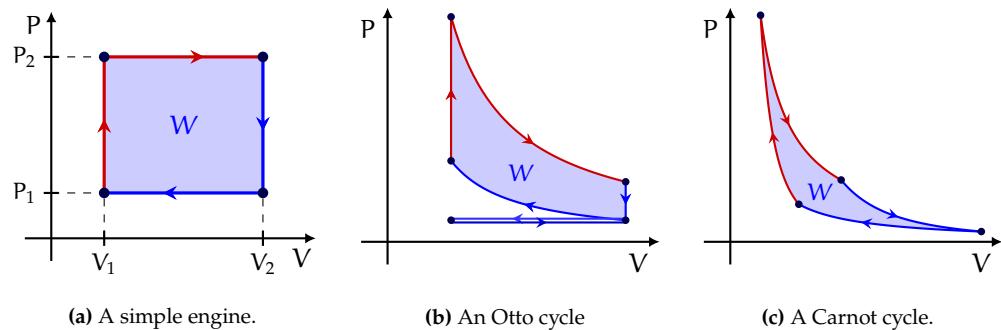


Figure 6.2: [10] Some thermodynamic cyclic processes.

# Circular Motion

- *Angular displacement* is the angle through which an object turns *with respect to the center of the circular path*.
- *The radian* is defined as the angle *subtended at the center* of a circle by an *arc* of length equal to the radius of the circle.
- *Angular velocity* is the rate of change of angular displacement.

|                                    |               |   |              |
|------------------------------------|---------------|---|--------------|
| $\omega = \frac{2\pi}{T} = 2\pi f$ | $v = r\omega$ | $a_c = \frac{v^2}{r} = r\omega^2 = v\omega$ | $F_c = ma_c$ |
|------------------------------------|---------------|---|--------------|

- Common formulae:  $\theta = \tan^{-1} \left( \frac{v^2}{rg} \right)$ ,  $v = \sqrt{rg}$ .
- Water in bucket at top position:  $F_c = N + W$  (where  $N \geq 0$ ) so  $\omega > \sqrt{\frac{g}{r}}$ .
- Need to write “Centripetal force is provided by \_\_\_\_\_”

# Gravitational Fields

- *Newton's Law of Gravitation* states that the force of attraction between any two point masses is directly proportional to the product of their masses and inversely proportional to the square of their separation.
- A *gravitational field* is a region in space where mass experiences a gravitational force acting on it.
- Gravitational field strength at a point is defined as the gravitational force per unit mass acting on a small mass placed at that point
- The *gravitational potential energy* of a mass at a point is defined as the work done by an *external agent* in bringing the mass *from infinity* to that point (without any net change in kinetic energy).
- *Gravitational potential* at a point is defined as the work done per unit mass by an *external agent* in bringing a mass *from infinity* to that point (without a change in kinetic energy).
- Escape velocity is the *minimum* velocity a mass needs to be projected from the *surface* of the moon in order to have sufficient kinetic energy to overcome the gravitational field it experiences and *move to infinity*.
- Escape velocity  $v_{\min} = \sqrt{\frac{2GM}{r}}$  (where Min  $E_k$  needed is the gain in  $E_p$  to reach infinity).

□

$$\begin{aligned} U_G &= -\frac{GMm}{r} \xrightarrow{-\frac{d}{dr}} F_G = -\frac{GMm}{r^2} \\ \downarrow \frac{1}{m} & \qquad \qquad \qquad \downarrow \frac{1}{m} \\ \phi &= -\frac{GM}{r} \xrightarrow{-\frac{d}{dr}} g = -\frac{GM}{r^2} \end{aligned}$$

- $U_G = m\phi$  &  $\Delta U_G = m\Delta\phi$ .
- $U_G$  is negative because infinity is taken as the reference point for zero potential energy. The work done against gravitational force in bringing a mass from infinity to that point is negative.
- Gravitational force provides the centripetal force:

$$\begin{aligned} F_G &= F_c \\ \frac{GMm}{r^2} &= mr\omega^2 = mr\left(\frac{2\pi}{T}\right)^2 \\ T^2 &= \frac{4\pi^2}{GM}r^3 \\ T^2 &\propto r^3 \end{aligned}$$

- Gravitational force provides the centripetal force:

$$\begin{aligned} F_G &= F_c \\ \text{For A: } \frac{Gm_A m_B}{(r_A + r_B)^2} &= m_A r_A \omega^2 \\ \text{For B: } \frac{Gm_A m_B}{(r_A + r_B)^2} &= m_B r_B \omega^2 \end{aligned}$$

The center of mass of the system is at point P where

$$m_A r_A = m_B r_B$$

such that both stars have the same angular velocity  $\omega$ .

- For binary star systems, notice that *orbital radius is replaced by the stars' separation*:

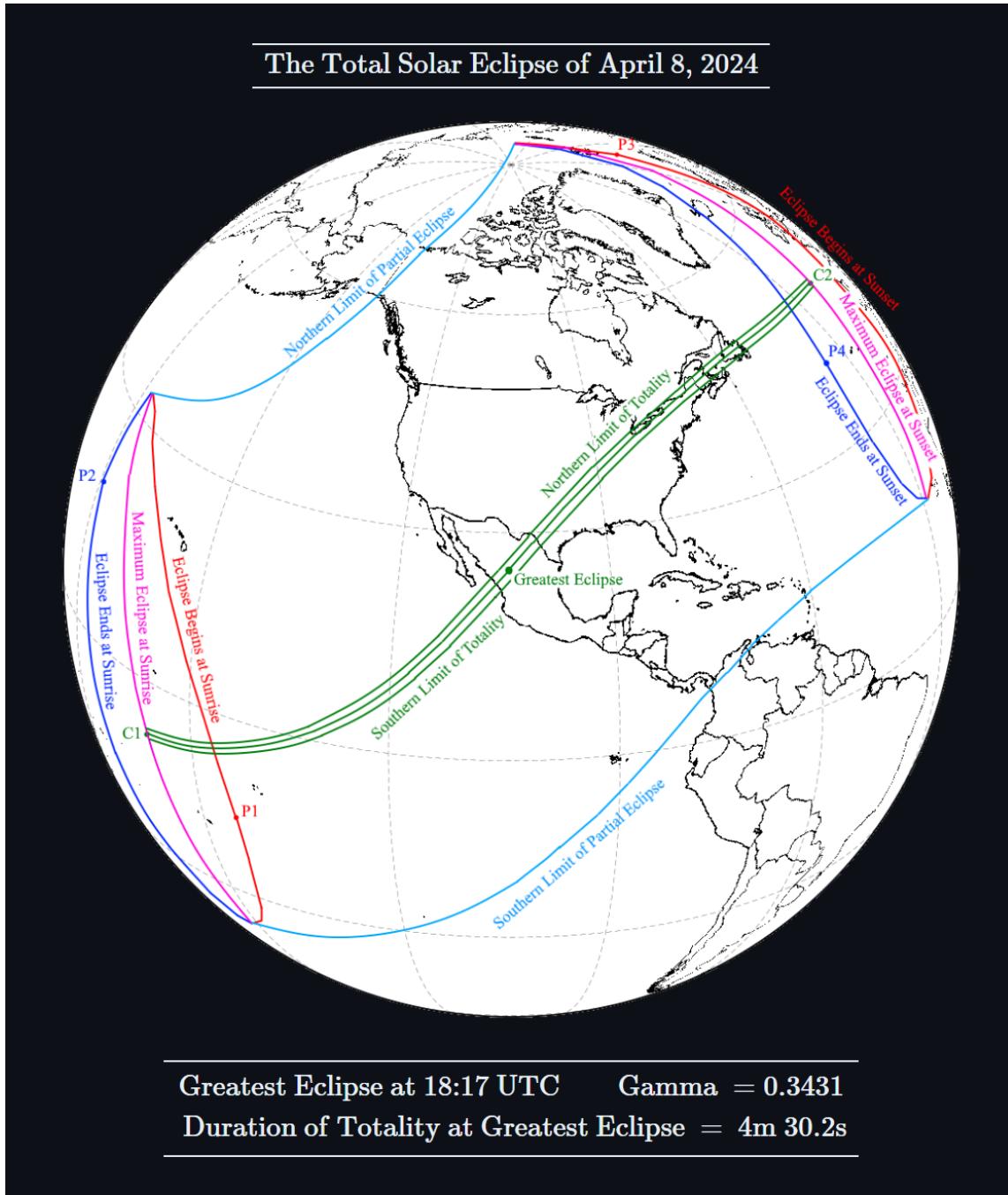
$$\begin{aligned} m_A r_A &= m_B r_B & \frac{G m_A m_B}{(r_A + r_B)^2} &= m_B r_B \omega^2 \\ r_A + r_B &= \frac{m_B}{m_A} r_B + r_B & \text{so} &= \frac{m_A m_B}{m_A + m_B} (r_A + r_B) \omega^2 \\ r_B &= \frac{m_A}{m_A + m_B} (r_A + r_B) \end{aligned}$$

So, rearranging, we have

$$\omega^2 = \frac{G(m_A + m_B)}{(r_A + r_B)^3} = \frac{G m_A}{r_B(r_A + r_B)^2} \quad \text{and} \quad T^2 = \frac{4\pi^2}{G(m_A + m_B)} (r_A + r_B)^3.$$

- Geostationary orbit facts:

1. Only one such orbit at a *fixed* distance of  $4.2 \times 10^7$ m from Earth's center,
  2. Orbital period of 24 hours,
  3. Satellite's plane of orbit coincides with the equatorial plane of the Earth,
  4. Orbits West to East (in the same direction as Earth's rotation).
- Equipotential lines are not equally spaced because the gravitational field strength is not constant but decreases as one goes away from the Earth.
  - Assumptions made in the theory (e.g. in deriving  $g = -\frac{GM}{r^2}$ ):
1. The bodies are separated by distances so large they can be considered as point particles (i.e. separation » radius).
  2. The bodies are homogenous spheres (constant density throughout the sphere).
  3. The bodies have masses distributed symmetrically around the center in uniform layers.
  4. In the absence of other masses.



**Figure 8.1:** [11] Forces acting on a crane.

*Note.* According to the author of this image, when compared to their above prediction,

1. The duration of eclipse at greatest eclipse is 2 seconds shorter.
2. The moments of contact are a couple seconds off.

# Oscillations

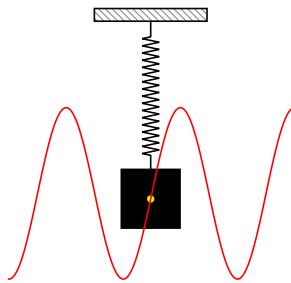
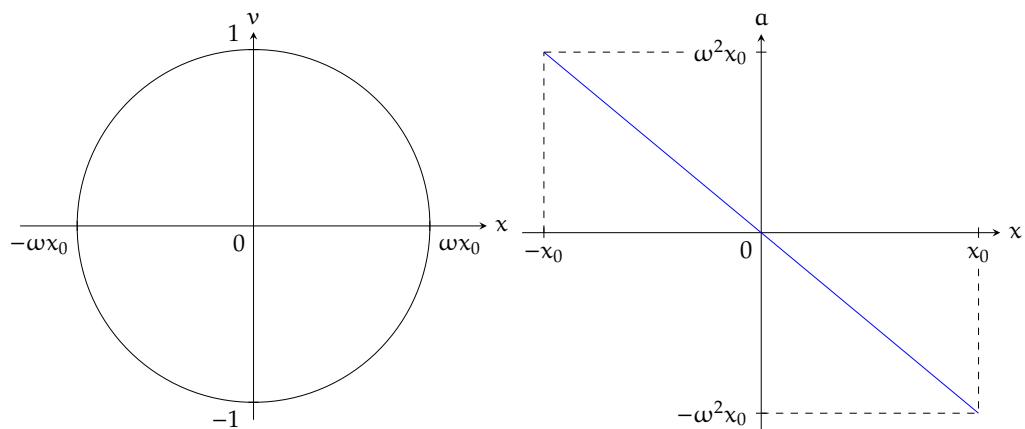


Figure 9.1: [12] Simple harmonic motion.

- *Simple harmonic motion* is defined as the motion of a body whose acceleration is directly proportional to its displacement from a fixed point (equilibrium position) and is always directed towards that fixed point.
- A *freely oscillating* system oscillates at its own *natural frequency* without *external influences* other than the *initial impulse when displaced* from its equilibrium position, with *no dissipation* of energy.
- *Damped oscillations* are oscillations in which the amplitude diminishes with time as a result of *dissipative forces* that reduce the total energy of the oscillations.
- A system is in *forced oscillations* when it is forced to oscillate at a frequency other than the natural frequency by a *periodic external force*.
- *Resonance* is a phenomenon that occurs when the frequency at which an object is being made to vibrate (the forced frequency of vibration) is equal to its natural frequency of vibration.

|                                   |                  |   |  |
|-----------------------------------|------------------|---|--|
| $v = \pm\omega\sqrt{x_0^2 - x^2}$ | $a = -\omega^2x$ | Spring-Mass<br>$T = 2\pi\sqrt{\frac{m}{k}}$ | Pendulum<br>$T = 2\pi\sqrt{\frac{l}{g}}$ |
|-----------------------------------|------------------|---|--|

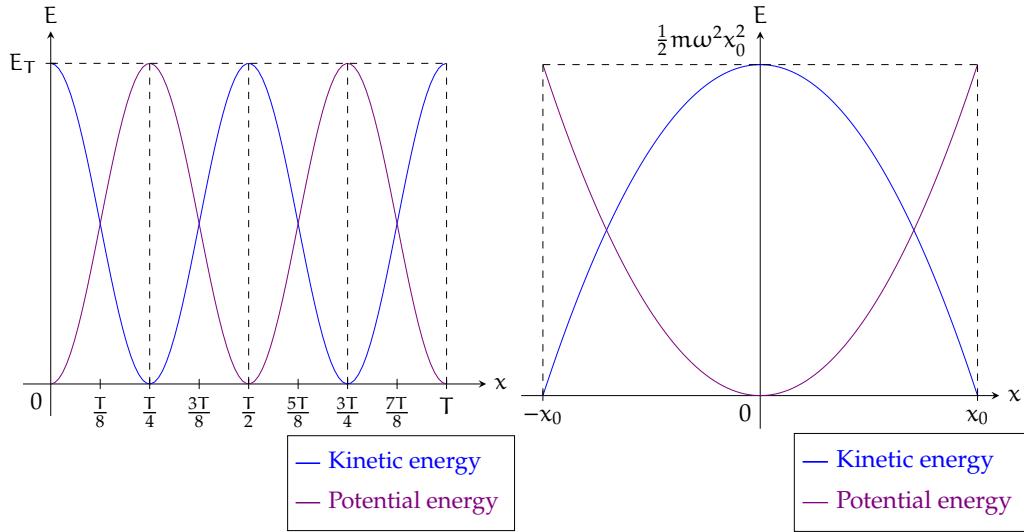


(a) Velocity against displacement.

(b) Acceleration against time.

Figure 9.2: [13] Graphs for velocity and acceleration.

|   | $E_k$  | $E_p$  | $E_T$                       |
|---|--|--|-----------------------------|
| t | $\frac{1}{2}m\omega^2x_0^2 \cos^2(\omega t)$ | $\frac{1}{2}m\omega^2x_0^2 \sin^2(\omega t)$ | $\frac{1}{2}m\omega^2x_0^2$ |
| m | $\frac{1}{2}m\omega^2(x_0^2 - x^2)$          | $\frac{1}{2}m\omega^2x^2$                    | $\frac{1}{2}m\omega^2x_0^2$ |



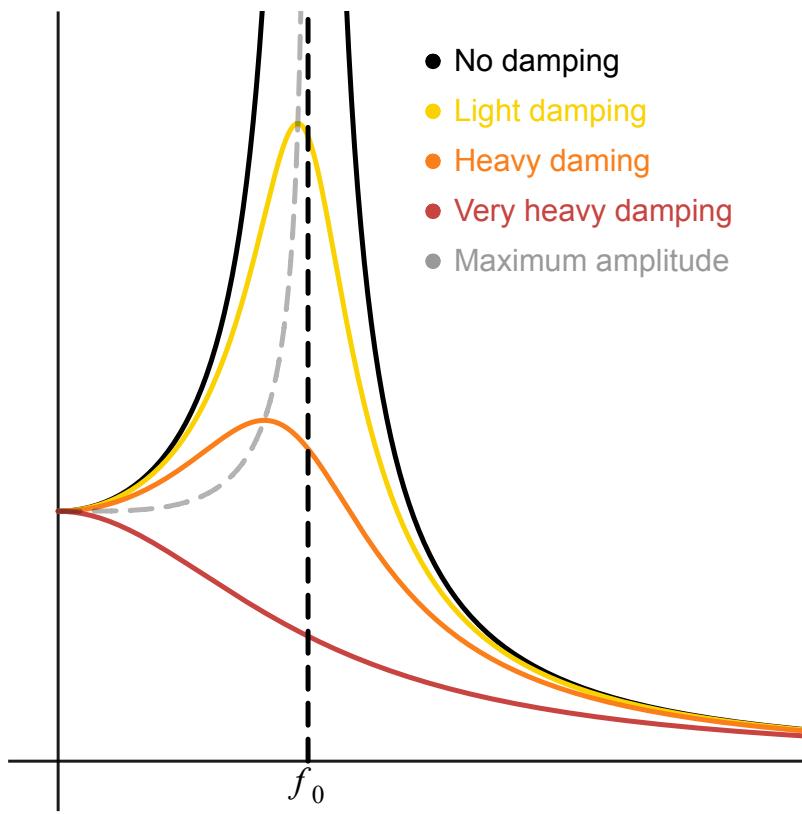
(a) Kinetic/potential energies against time. (b) Kinetic/potential energies against displacement.

Figure 9.3: [13] Graphs for kinetic/potential energies.

- Simple pendulums and mass spring systems can be approximated to be SHM when the angle of oscillation ( $\leq 20^\circ$ ) and oscillation amplitude are small, respectively.

|                         | In Phase | Antiphase | Out of Phase |
|-------------------------|----------|-----------|--------------|
| $\Delta\phi/\text{rad}$ | 0        | $\pi$     | nonzero      |

- When damping increases:
  - Amplitude at *all* frequencies decreases.
  - (Resonance) frequency at max amplitude shifts gradually to lower frequencies.
  - Peak (max amplitude) becomes flatter.



**Figure 9.4:** [14] The graph of amplitude against frequency, as damping increases. The resonance frequency is denoted by  $f_0$ .

# Wave Motion

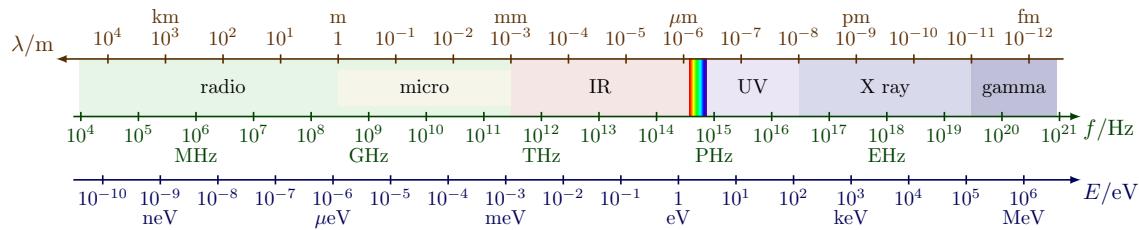


Figure 10.1: [16] The electromagnetic spectrum.

- A *progressive wave* is a wave in which *energy is carried* from one point to another by means of *vibrations or oscillations* within the wave. Particles within the wave are *not transported along* the wave.
- A *phase* is an angle which gives a measure of the *fraction of a cycle* that has been *completed* by an oscillating particle or by a wave.
- *Intensity* of a wave is the wave energy incident per unit time per unit area *normal* to the wave.
- *Polarisation* of a wave refers to the *confinement* of oscillations in *only* one plane. The plane of oscillations is *parallel* to the direction of energy transfer.

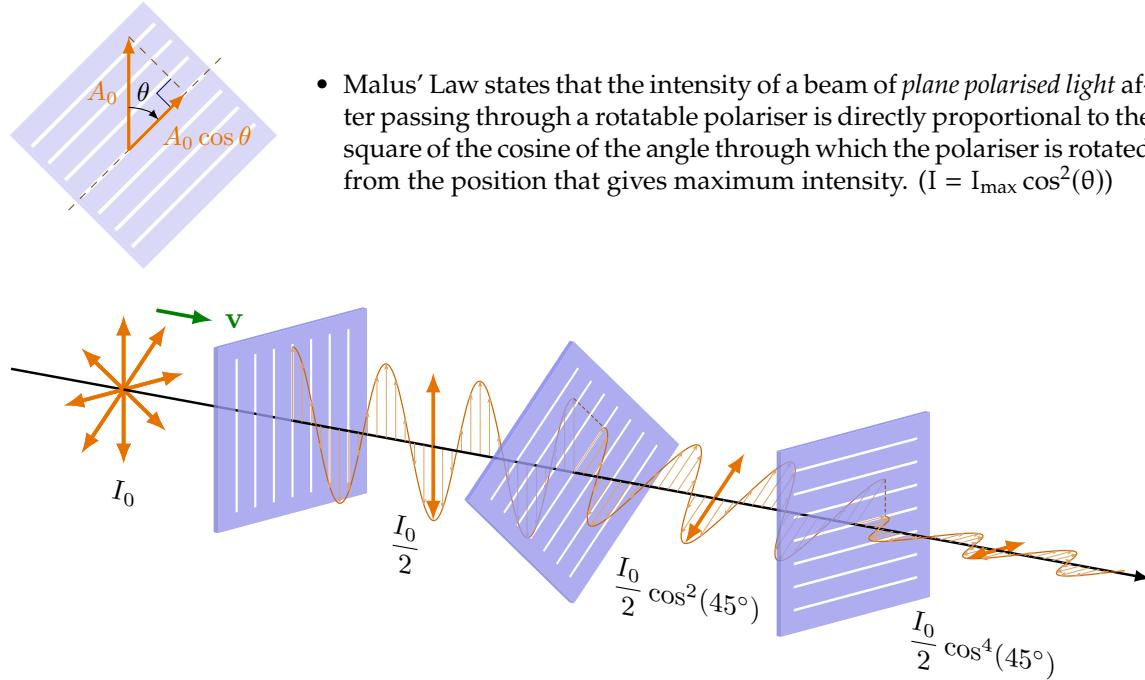


Figure 10.2: [17] An illustration of Malus' Law.

|                          |                               |                                |                          |
|--------------------------|-------------------------------|--------------------------------|--------------------------|
| <input type="checkbox"/> | Phase Difference $\Delta\phi$ | $\frac{2\pi}{\lambda}\Delta x$ | $\frac{2\pi}{T}\Delta t$ |
|--------------------------|-------------------------------|--------------------------------|--------------------------|

| □ | Intensity       |                           |                         |  |
|---|-----------------|---------------------------|-------------------------|--|
|   | Amplitude       | Wave                      |                         |  |
|   |                 | Spherical                 | Circular                | Plane                                    |
|   | $I \propto A^2$ | $I \propto \frac{1}{r^2}$ | $I \propto \frac{1}{r}$ | I is constant<br>(No spreading of waves) |

- ☆ When unpolarised light passes through a polariser, the average value of  $\cos^2(\theta)$  is  $\frac{1}{2}$  so  $I_{\text{new}} = \frac{1}{2} I_{\text{max}}$ .

# Superposition

- *Principle of Superposition:* When two or more waves of the *same type*, meet at a point in space, the resultant displacement of the waves at that point is the *vector sum* of the *displacements* due to each wave acting independently at that point.
- *Stationary waves* are waves whose *waveforms do not advance* and where there is *no net translation of energy*. The *amplitude* of the waves varies according to *position* from zero at the nodes to a maximum at the antinodes.
- A stationary wave is formed when two *progressive* waves
  1. Having the *same frequency* and *same speed*
  2. Travel in *opposite directions* towards each other
  3. Have *similar amplitudes*
  4. Are unpolarised, or polarised along the same axis
  5. Are *superposed*

|   | Properties | Reflection Surface     |           |
|---|------------|------------------------|-----------|
|   |            | Loose End <sup>1</sup> | Fixed End |
| • Allows for Oscillations?                                |            | Yes                    | No        |
| Will Reflected Wave be Inverted (phase change of $\pi$ )? |            | No                     | Yes       |

- Characteristics of Stationary Waves:

1. Displacement node = Pressure antinode
2. Displacement antinode = Pressure node

| Properties                                 | Stationary Wave   | Progressive Wave   |
|--|---|--|
| Energy                                     | No net transfer of energy   | Energy is transferred in the direction of propagation of the wave. |
| Phase                                      | <input type="checkbox"/> Adjacent nodes: In phase<br><input type="checkbox"/> Adjacent segments: Antiphase.<br>(Fig 12.1) | All points within one wavelength have different phases.            |
| Amplitude                                  | Varies: 0 at nodes to max at antinodes.   | Same for all particles.  |
| Wavelength                                 | Twice the distances between adjacent nodes or adjacent antinodes.   | Distance between adjacent in-phase particles.                      |
| Frequency                                  | Same for all particles  |  |
| Nodes <sup>2</sup> /Antinodes <sup>3</sup> | ✓   | ✗  |

<sup>1</sup>Particles of the wave can move about freely.

<sup>2</sup>At which particles don't oscillate/amplitude = 0.

<sup>3</sup>At which particles have the largest amplitude.

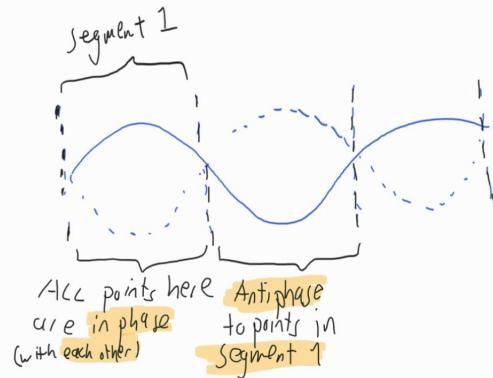


Figure 11.1: [18] Phases in stationary waves

|                         | Modes           |                        | Diagrams    | Wavelength                  | Frequency                   |
|-------------------------|-----------------|------------------------|-------------|-----------------------------|-----------------------------|
|                         | Overtone        | Harmonic               |             |                             |                             |
| Strings/Open Pipes      | n <sup>th</sup> | (n + 1) <sup>th</sup>  | 12.2 & 12.3 | $\lambda = \frac{2L}{n+1}$  | $f = (n + 1) \frac{v}{2L}$  |
| Pipes Closed at One End |                 | (2n + 1) <sup>th</sup> | 12.4 & 12.5 | $\lambda = \frac{4L}{2n+1}$ | $f = (2n + 1) \frac{v}{4L}$ |

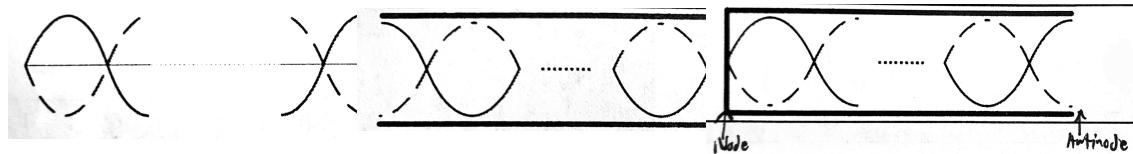


Figure 11.2: [15] String.

Figure 11.3: [15] Open pipe.

Figure 11.4: [15] Pipe closed at one end

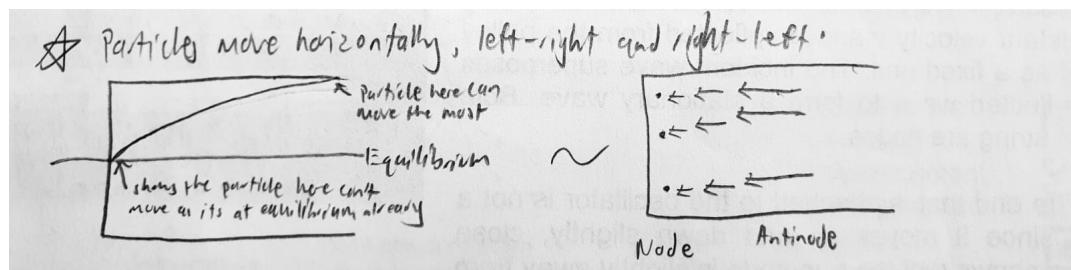


Figure 11.5: Movement of particles in pipe.

- Resonance length<sup>2</sup> with pipes closed at one end

$$L = \frac{\lambda}{4} = \frac{v}{4f}.$$

<sup>2</sup>End correction: Actual length of vibration is L + 2c for open pipes, and L + c for closed pipes.

**Example 11.1**

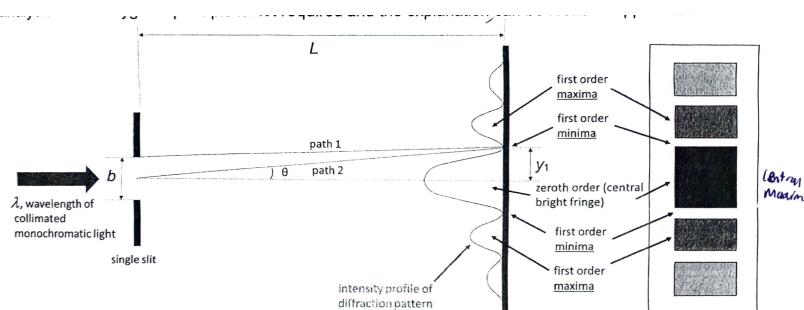
Explain, with reference to resonance, why the loudness of sound changes as the water level changes.

1. Natural frequency of vibration depends on length of air column.
  2. When fork frequency is equal to natural frequency/odd multiple of fundamental frequency, resonance occurs. There is maximum energy transfer and maximum amplitude of vibrations, leading to maximum loudness.
  3. When fork frequency is not equal to natural frequency, no resonance occurs and loudness drops.
- If a tube achieves stationary waves at fundamental frequency  $f$ , then reducing  $f$ /increasing  $\lambda$  will not result in stationary waves.
  - *Diffraction* is the *bending or spreading out* of waves when they travel through a *small opening* or when they pass round a *small obstacle*.
  - Large amount of diffraction occurs when the width of slit is about the same as the wavelength.
  - The wavelength before and after diffraction should be around the same.
  - Single Slit Diffraction: Let  $b$  be the slit width, and  $L$  the slit-screen distance.
    1. For all nonzero integers  $m$ , the angular positions  $\theta$  of the  $1 \leq m \leq m$ th order minima satisfies

$$\sin(\theta) = \frac{m\lambda}{b}.$$

2. Distance  $y_1$  of the first minima from either side of the central bright fringe is

$$y_1 = \frac{\lambda L}{b}.$$



**Figure 11.6:** [15] Single slit diffraction.

- Circular aperture:  $\theta \approx \frac{\lambda}{b}$ .
- Rayleigh's Criterion is the minimum separation between two objects in order to be distinguished as two distinct objects:

$$\theta \approx \frac{\lambda}{b}.$$

- Sources are *coherent* if they have a *constant phase difference* with respect to time.
- *Interference* is the *superposing* of two or more waves to produce *regions of maxima and minima* in space, according to the *Principle of Superposition*.

- Conditions for an *observable* interference pattern:
  1. The waves must *overlap* to produce regions of maxima and minima.
  2. The *sources* must be *coherent*.
  3. The waves must have approximately the *same amplitude*.
  4. The waves, if transverse, must be *unpolarised* or have the *same plane of polarisation*.
- For  $n \in \mathbb{Z}_0^+$ , representing the  $n$ th order max/min, we have

| Sources' Phase Difference | Path Difference                    |                                   |
|---------------------------|------------------------------------|-----------------------------------|
|                           | Constructive Interference (maxima) | Destructive Interference (minima) |
| In phase                  | $\Delta = n\lambda$                | $\Delta = (n + 1/2)\lambda$       |
| Out-of-phase              | $\Delta = (n + 1/2)\lambda$        | $\Delta = n\lambda$               |

- We always need to take the path difference starting from the actual source itself, even when the source travels through two slits onto a screen, for instance.
- Double-slits: For<sup>3</sup> a (*center-to-center*) slit separation  $a$  and slit-screen distance  $D$ , the fringe separation (between two adjacent minima, or two adjacent maxima) is

$$x = \frac{\lambda D}{a}.$$

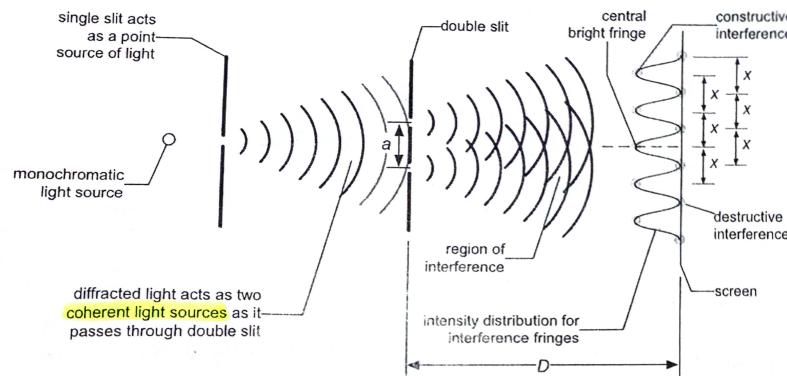


Figure 11.7: [15] Double-slit diffraction.

- Diffraction grating: For a slit-separation  $d$  and  $n \in \mathbb{Z}_0^+$ , the angular positions for the  $n$ th order maxima satisfies

$$d \sin(\theta_n) = n\lambda.$$

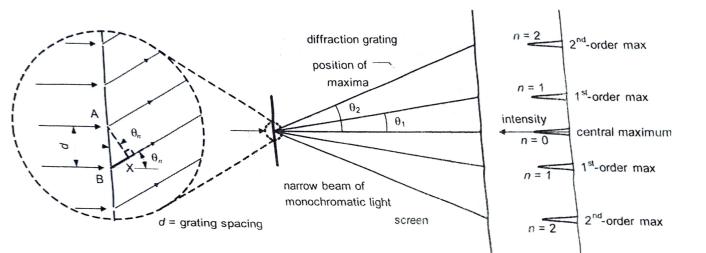


Figure 11.8: [15] Diffraction grating.

<sup>3</sup>Typical values:  $a \approx 0.5\text{mm}$ ,  $D \approx 1\text{m}$ , and  $\lambda \approx 600\text{nm}$ . In any case, using the equation requires  $a \ll D$ .

<sup>4</sup>The intensity of the double-slit interference pattern is not constant because of single-slit diffraction effects.

- Check answer: For visible light,  $400\text{nm} \leq \lambda \leq 700\text{nm}$ .
- Total number of bright regions = 2·highest order+1.
- When slit width is reduced, intensity is reduced.
- To calculate *resultant intensity*, first take the sum of the amplitudes and use proportionality ( $I \propto A^2$ ).
- Every other line means half of the lines are covered.

**Example 11.2**

Describe and explain the appearance of the central fringe if the light is now replaced with white light.

1. The central bright fringe is generally white.
2. The zeroth order fringes of all the wavelengths coincide at the center where the path difference from the two slits is zero for all wavelengths. The combined central fringes remains white.
3. The sides of the central fringes are likely more reddish.
4. This is because the wider red fringe extends beyond the narrower blue fringe.

# Currents of Electricity

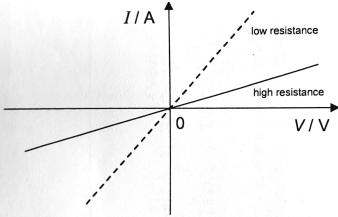
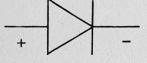
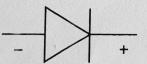
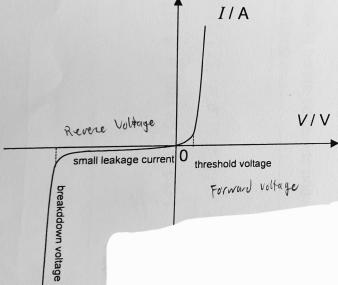
- The *number density*  $n$  is defined as the number of particles per unit volume.
- The *drift velocity*  $v$  is the *average* velocity at which *charge carriers* move through a *conductor* when there is *electric current in the conductor*.
- Deriving the equation  $I = nAvq$ :
  1. Assume that the *current is constant*. Then,  $I = \frac{Q}{t}$ . [n]
  2. Assume that there are  $N$  charge carriers passing through a cross-sectional area  $A$  in time  $t$ , and that *each* of them carries an *identical amount of charge*  $q$ . Then, the *total charge* that passing through  $A$  in time  $t$  is  $Q = Nq$ . [N, A(t), Q(t)]
  3. Assume that the *number density*  $n$  of charge carriers is *uniform*, and let  $V$  be the volume covered by the current in time  $t$ . Thus,  
$$N = nV. \quad [n, V(t)]$$
  4. Furthermore, since the current travels at some velocity  $v$ ,

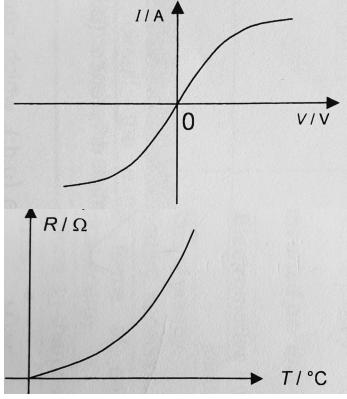
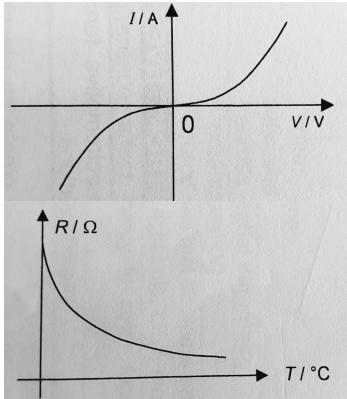
$$V = A\Delta x = Avt. \quad [v]$$

- 5. Therefore,
- $$I = \frac{Q}{t} = \frac{Nq}{t} = \frac{nVq}{t} = \frac{nAvtq}{t} = nAvq.$$
- Elementary charge  $e = 1.6 \times 10^{-19} C$  (Charge of an electron/proton).
  - The *potential difference* between *two points* of a circuit is defined as the amount of electrical energy *converted* to other forms of energy *per unit charge* moved *between* the two points.
  - *Ohm's Law* states that the *current* flowing in a *conductor* is *directly proportional* to the *potential difference across it* under *constant physical conditions*.
  - *Resistance* is defined as the *ratio* of the *potential difference* across the conductor to the *current* flowing through it.
  - *Resistivity*  $\rho$  is the *proportionality constant* between the *dimensions of a specimen of a material* and its *resistance* such that

$$R = \frac{\rho L}{A}.$$

- Electrical Components

| Types of Conductors                        | Changes to Resistance  | Reason   |
|--|--|--|
| Metallic conductor at constant temperature | <ul style="list-style-type: none"> <li>At <i>constant temperature</i> this is an <i>Ohmic conductor</i>.</li> <li>Has <i>constant resistance</i>. Ratios of <math>V/I</math> is constant.</li> </ul>    | <ul style="list-style-type: none"> <li>At <i>constant temperature</i>, the <i>number of free electrons</i> and the <i>rate of atomic vibration</i> is constant.</li> <li>A resistor at a different constant temperature will have a different resistance, and hence, <math>V/I</math> ratio.</li> </ul>  |
| Semiconductor Diode                        | <p><b>Forward-biased (+ve V):</b></p>  <p>Conducting</p> <p><b>Reverse-biased (-ve V):</b></p>  <p>Not conducting</p> <ul style="list-style-type: none"> <li>Forward-biased: <i>Resistance decreases when p.d. increases</i>. In fact, if the forward-biased p.d. goes past its <i>threshold voltage</i>, resistance becomes very low.</li> <li>Reverse-biased: <i>Very high resistance</i>. But, there will be a <i>small leakage current</i>.</li> <li>If the reverse-biased p.d. is so high that it exceeds the <i>breakdown voltage</i>, the diode will <i>break down</i> and <i>conduct electricity</i>.</li> </ul>  | <ul style="list-style-type: none"> <li>When connected in <i>forward bias</i>, the circuit's electric field set up allows for available charge carriers to flow through, allowing it to conduct with <i>low resistance</i>.</li> <li>When connected in <i>reverse bias</i>, the circuit's electric field set up creates a <i>widened 'depletion region'</i> in the diode which <i>impedes charge carriers</i> from flowing through the region, creating a <i>large resistance</i>.</li> </ul> |

|  |  |  |
|--|--|--|
| <p>Filament Lamp</p>                                     | <ul style="list-style-type: none"> <li>- When p.d. increases, current increases, with decreasing I-V ratio.</li> <li>- The resistance of a metallic conductor increases with an increase in temperature.</li> </ul>   | <ul style="list-style-type: none"> <li>- As current increases, power dissipated increases since <math>P = I^2R</math>. Heat is generated so equilibrium temperature rises—as electrons drift through the metal, they collide with the metal lattice and transfers energy to it.</li> <li>- The lattice ions vibrate more vigorously. This hinders the flow of 'charge carriers'. Therefore, resistance is increased.</li> <li>- Ohmic conductors hence do not obey Ohm's Law at high voltages/currents.</li> </ul>   |
| <p>Negative Temperature Coefficient (NTC) Thermistor</p> | <ul style="list-style-type: none"> <li>- When p.d. increases, current through the thermistor also increases, with increasing I-V ratio.</li> <li>- The resistance of a thermistor decreases with an increase in temperature (This is the meaning of NTC).</li> </ul>  | <ul style="list-style-type: none"> <li>- As current increases, power dissipated increases. More heat is generated, leading to a rise in equilibrium temperature.</li> <li>- Thus, the mean kinetic energy of the electrons and lattice ions increases. So,             <ol style="list-style-type: none"> <li>1. The bonded electrons break free from bonds, increasing the number of 'mobile charge carriers'. Therefore, resistance decreases.</li> <li>2. The lattice ions vibrate more vigorously, hindering the flow of 'mobile charge carriers'. Thence, resistance increases.</li> </ol> </li> <li>- The first effect is much more significant than the second. So, there is a net decrease in resistance.</li> </ul> |

The images above come from [15].

- The *electromotive force* (e.m.f) of a *source* is defined as the amount of *energy converted* from *non-electrical forms of energy* to *electrical energy per unit charge* as the *charge passes through a complete circuit*.
- Internal resistance: the p.d. across a component is given by  $V = E - Ir$ .
- Power dissipated  $P = IV$ .
- Power delivered is *maximum* when  $R = r$ , such that

$$P_{\max} = \frac{E^2}{4r}$$

- Efficiency of the source
    - *Increases* when external load/*resistance increases*.
    - Is halved when  $R = r$ .
- Note:* Maximum power  $\neq$  maximum efficiency.

# Electric Fields

- Coulomb's Law states that the *magnitude* of the *electric force* between two *point charges* is directly proportional to the product of the charges, and inversely proportional to the square of their separation.
- The constant  $\epsilon_0$  is the permittivity of *free space* ( $\epsilon_0$  is applicable only in air or a vacuum).
- Sign of  $F_E$ :

| $F_E$    | Direction  |
|----------|------------|
| Positive | Repulsive  |
| Negative | Attractive |

- The sign of the electric force does *not* represent the *direction* of the electric force. It only informs us whether the force is attractive or repulsive. So, when calculating the *resultant* electric force, we need to account for the direction ourselves.
- Comparison between E-fields and G-fields:

| Sim/Diff | E-field   | G-field   |
|----------|---|---|
| S        | For both Coulomb's Law and Newton's Law of Gravitation, $r$ is the <i>center to center separation</i> of the objects.                         |   |
| S        | By Newton's Third Law, the <i>forces</i> that masses and charges exert on each other is <i>equal in magnitude and opposite in direction</i> . |   |
| D        | Electric Forces can be <i>attractive or repulsive</i> .   | Gravitational forces are <i>always attractive</i> . |

- An *electric field* is a *region in space* where a *charge experiences an electric force*.

- How to draw electric field lines:

- Lines cannot intersect one another.
- Lines must begin from positive charges and end on negative charges.
- Arrows show the *direction of force* exerted on a positive test charge.
- The *greater* the electric field strength, the *closer together* field lines are drawn.
- Lines leave/end on *conducting surfaces* at *right angles*

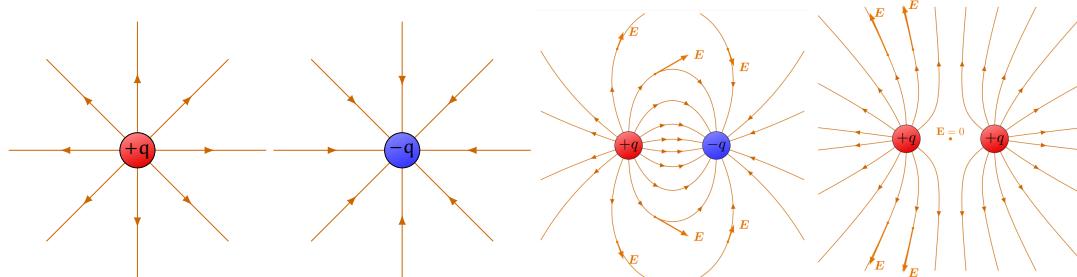
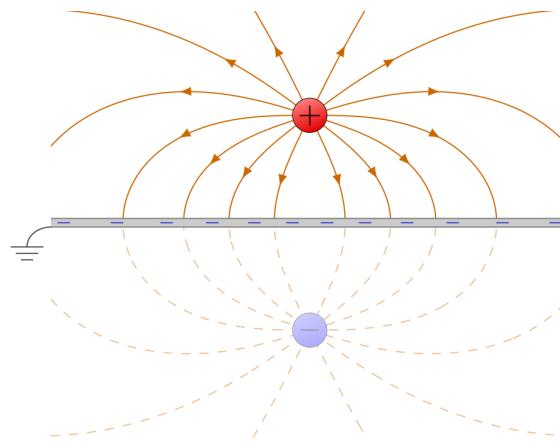
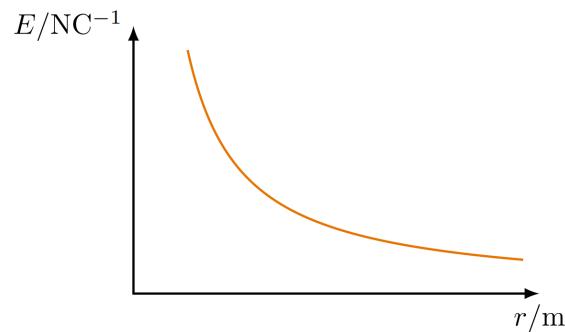


Figure 13.1: [19], [20] Electric field lines of point charges and two interacting charges.



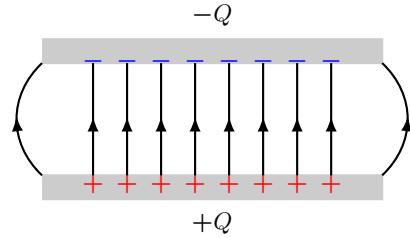
**Figure 13.2:** [21] Interaction of a point charge with a charged plate.

- The *electric field strength* at a point is defined as the *electric force per unit positive charge* acting on a small stationary test charge placed at that point.



**Figure 13.3:** [22] Electric field strength of a positive point charge

- Charge distribution on a conducting sphere:
  - Excess charges are forced to the surface of the conductor until the electric field inside the conductor is zero.
  - Outside the conductor, the electric field is the *same* as that of an isolated point charge equal to the excess charge.
- Properties of conductors in *electrostatic equilibrium*:
  - The *electric field is zero inside* a conductor (regardless of shape).
  - So, the *entire conductor* is at the *same potential*.
  - Just outside the conductor, the e-field lines are *perpendicular to its surface*, starting and ending on charges on the surface.
  - Excess charges* resides exclusively on the *surfaces* of a conductor.
- Electric field strength between two charged parallel plates is uniform everywhere between the plates, except at both ends of the plates.
- Also, *charges* between the plates experience *uniform acceleration*.



**Figure 13.4:** [23] Electric field lines between parallel plates.

- Magnitude of electric field strength between the plates:

$$E = \frac{dV}{dr} = \frac{\Delta V}{d}.$$

- The *electric potential energy* of a point charge in an electric field is defined as the *work done by an external agent* in bringing the point charge from infinity to that point (without any net change in kinetic energy).
- The *electric potential* at a point in an electric field is defined as the *work done per unit positive charge*, by an external agent, in bringing a *small* test charge from infinity to that point (without any net change in kinetic energy).
- Let  $U$  be the electric potential energy, and  $V$  the electric potential. Then,

$$U = qV \quad \text{and} \quad \Delta U = q\Delta V.$$

•

$$\begin{aligned} U &= \frac{Qq}{4\pi\epsilon_0 r} \xrightarrow{-\frac{d}{dr}} F_E = \frac{Q_1 Q_2}{4\pi\epsilon_0 r^2} \\ &\quad \downarrow \frac{1}{q} \qquad \qquad \downarrow \frac{1}{q} \\ V &= \frac{Q}{4\pi\epsilon_0 r} \xrightarrow{-\frac{d}{dr}} E = \frac{Q}{4\pi\epsilon_0 r^2} \end{aligned}$$

- The *electric potential* at a point  $X$  due to a *system* of point charges  $q_i$  is the algebraic sum of the electric potential  $V_i$  due to each individual charge  $q_i$  which is distance  $r_i$  away from  $X$ . That is,

$$V = \sum_i V_i = \sum_i \frac{q_i}{4\pi\epsilon_0 r_i}.$$

- The *potential energy* of a *system* of charges  $q_i$  is the work done to assemble it. This is the sum of energies  $U_{ij}$  needed to bring each charge  $q_i$  to the charges  $q_j$  (for  $i > j$ ) already present. In other words letting  $r_{ij}$  be the distance of  $q_i$  from  $q_j$ , we have

$$U = \sum_{i>j} U_{ij} = \sum_{i>j} \frac{q_i q_j}{4\pi\epsilon_0 r_{ij}}.$$

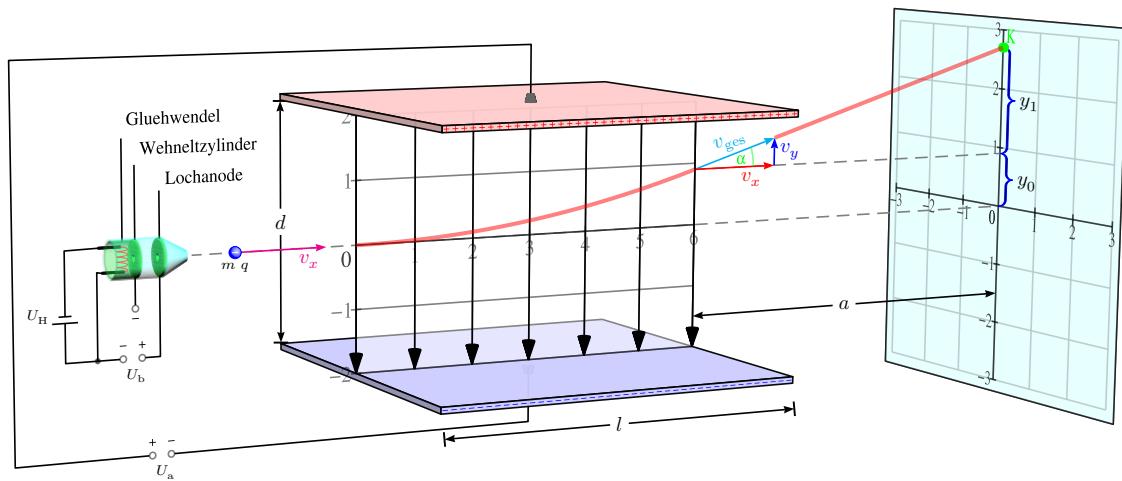


Figure 13.5: [24] Deflection of an electron.

# D.C. Circuits

- An explanation for how energy is transferred in a circuit: [Stack Exchange](#).

| Property   | Series   | Parallel   |
|------------|--|--|
| Current    | $I_1 = I_2 = \dots = I_n$                        | $I_i = \frac{E}{R_i}$  |
| Resistance | $R_{\text{effective}} = R_1 + R_2 + \dots + R_n$ | $\frac{1}{R_{\text{effective}}} = \frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_n}$ |
| Voltage    | $V_i = \frac{R_i}{R_T} \cdot E$                  | $E = V_1 = V_2 = \dots = V_n.$   |

- For  $n$  identical resistors in parallel, which are each of resistance  $R$ , we have  $R_{\text{effective}} = R/n$ . Furthermore, the effective resistance is at most the resistance of the smallest resistor, i.e.  $R_{\text{effective}} \leq R_i$  for each  $i$ . In fact, the inequality is strict when the number of resistors in parallel  $n \geq 2$ .
- To resolve tricky systems of resistors, use the fact that electric potential is constant along a wire.

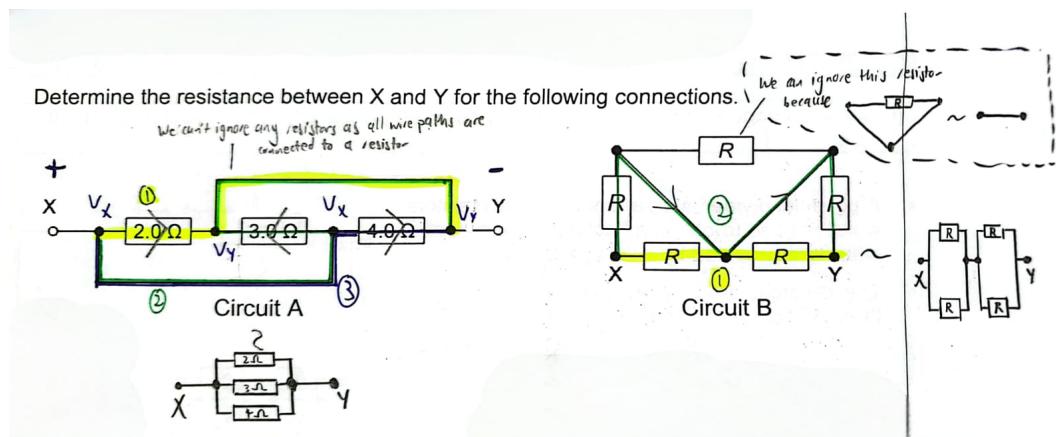
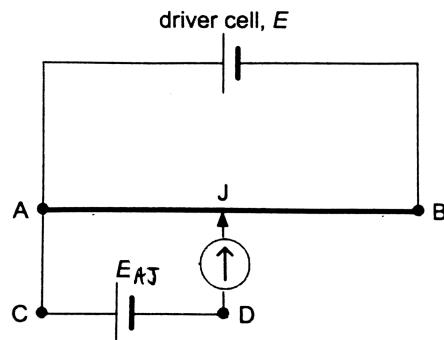


Figure 14.1: [15] Some tricky circuits.

- Potentiometer:
  - E.m.f. of driver cell is more than that of the unknown cell,  $E$ .
  - The direction of charge flow for the primary and secondary circuits are opposite. i.e. the positive/negative terminals should 'point' towards each other.
  - The potential difference  $V$  across length  $L$  of a resistance wire is directly proportional to  $L$ .
  - Consider the following circuit. When the galvanometer reads zero, the e.m.f. of the unknown cell is  $E_{AJ}$ , where

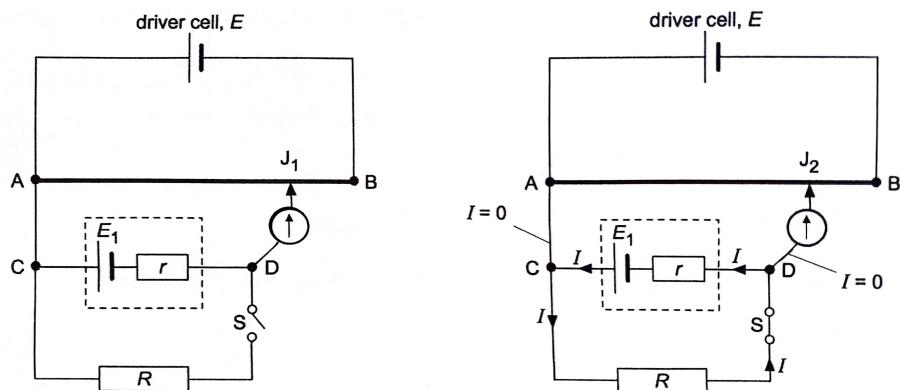
$$\frac{E_{AJ}}{E} = \frac{L_{AJ}}{L_{AB}} = \frac{R_{AJ}}{R_{AB}}.$$



**Figure 14.2:** [15] An illustration of a potentiometer.

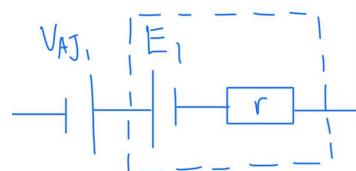
- In the circuit below, the internal resistance  $r$  satisfies

$$\frac{L_{AJ_2}}{L_{AJ_1}} = \frac{R}{R+r}.$$



**Figure 14.3:** [15] Some more illustrations of potentiometers.

For the diagram to the left, why  $V_{CD} = V_{AJ_1}$  is easily seen from the diagram below.



**Figure 14.4:** [18] Part CD of the circuit.

# Electromagnetism

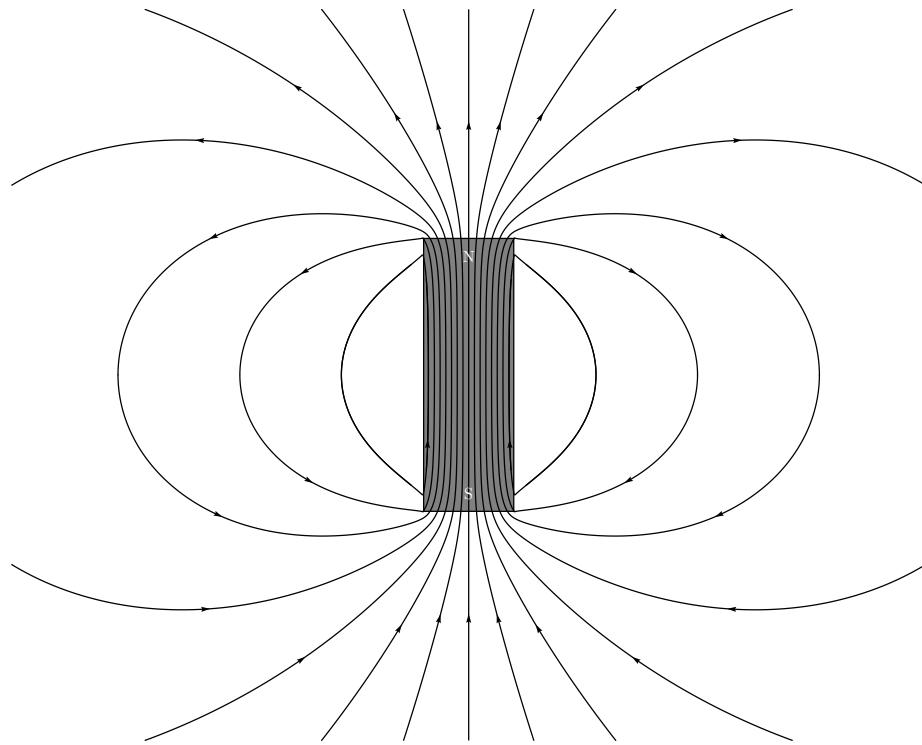
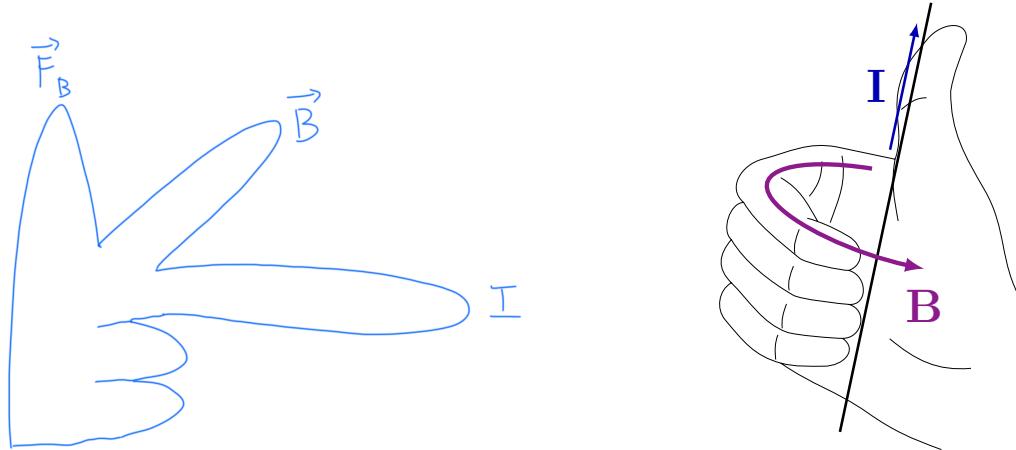


Figure 15.1: [25] Magnetic field produced by a bar magnet.

- A *magnetic field* is a *region of space* where a magnetic pole, moving charged particle or current-carrying conductor will *experience a magnetic force*.
- Normally, a magnetic field points from north-to-south. However, *inside* a magnet, the magnetic field points south-to-north.
- *Magnetic flux density* is defined as the *force per unit current per unit length* acting on an *infinitely long current-carrying conductor* placed *perpendicularly* to the magnetic field.
- Dots and crosses as indicators of direction:

|  |                 |
|--|-----------------|
|  | Into the page   |
|  | Out of the page |

- Left and right hand rules:

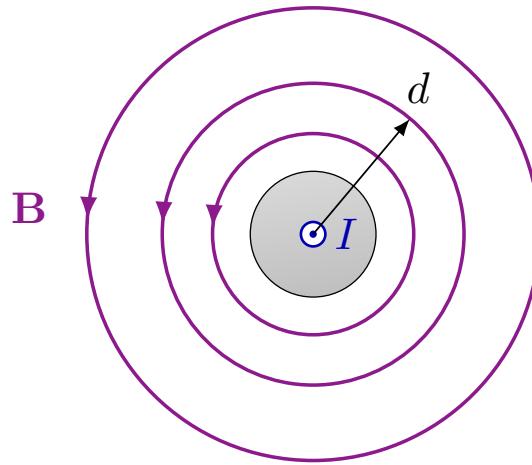


**Figure 15.2:** [27] Left and right hand rules.

- At any point some perpendicular distance  $d$  from the center of an *infinitely long straight* current-carrying conductor, the magnitude of the magnetic flux is given by

$$B = \frac{\mu_0 I}{2\pi d}.$$

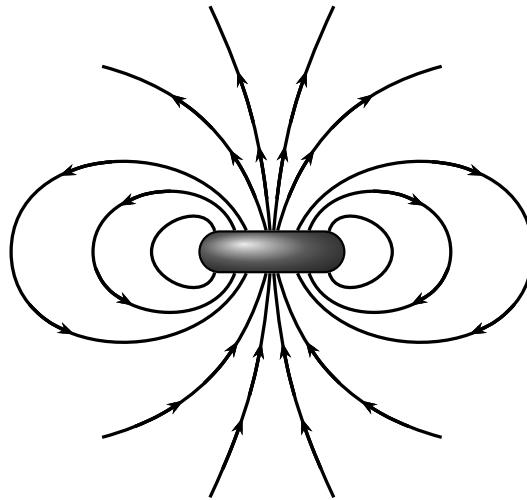
Here,  $\mu_0 = 4\pi \cdot 10^{-7}$  is the permeability of free space.



**Figure 15.3:** [26] Current in a wire.

- At the center of a flat circular coil with  $N$  turns, radius  $r$ , and current  $I$  flowing through it, the magnitude of the magnetic flux density is given by

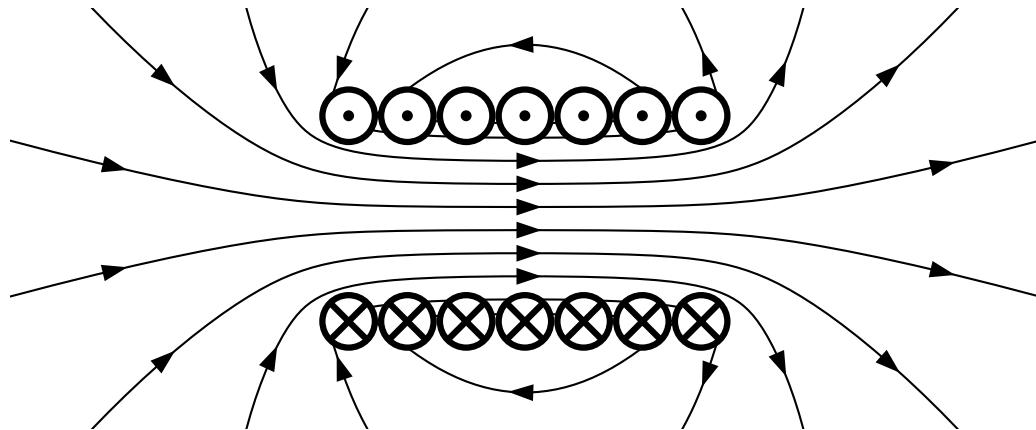
$$B = \frac{\mu_0 N I}{2r}.$$



**Figure 15.4:** [28] Current in a flat circular coil.

- Suppose we have an ideal (having infinite length) solenoid of  $n = N/L$  number of turns per unit length, which has a current  $I$  flowing through it. Then, the magnitude of the uniform magnetic flux density at its center is given by

$$B = \mu_0 n I.$$



**Figure 15.5:** [29] Current in a solenoid and the magnetic field produced.

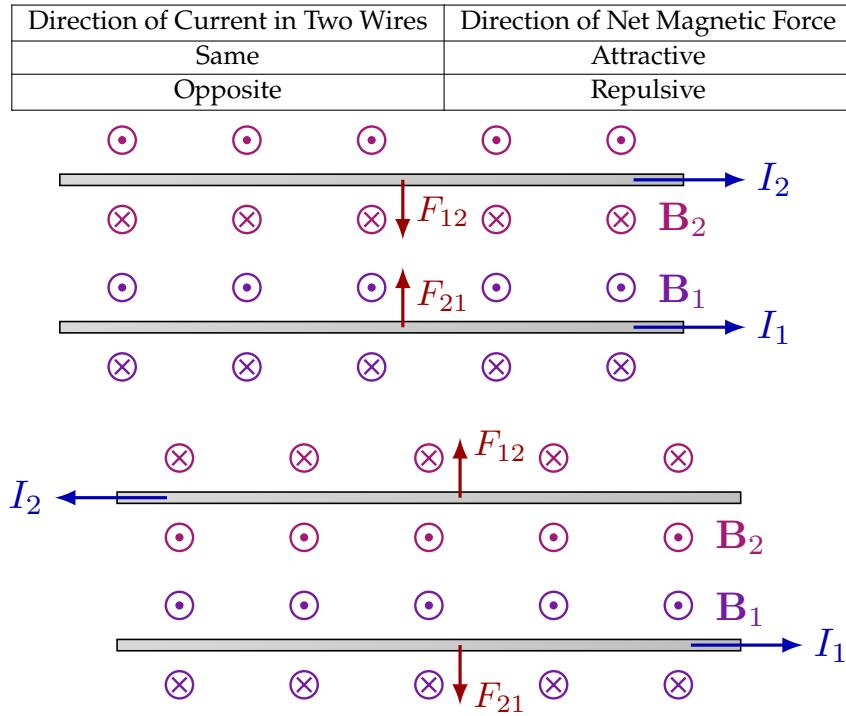
- A set of coils can be considered to be a solenoid when the radius of said coils is negligible compared to their length.
- The addition of a ferrous core, of permeability  $\mu$ , into a solenoid increases the magnetic flux density there, which is given by

$$B = \mu n I.$$

- Say we have a straight current-carrying conductor of length  $l$  with current  $I_{\perp}$  flowing perpendicular to the magnetic field. Then for any point on that conductor that experiences a magnetic flux of density  $B$ ,

$$F_B = BI_{\perp}l.$$

•



**Figure 15.6:** [30] Current carrying conductors in parallel.

- A charge  $q$  moving at speed  $v_{\perp}$  perpendicular to the magnetic field, of flux density  $B$ , experiences a magnetic force of magnitude

$$F_B = qv_{\perp}B.$$

- Notice that the charged particle above travels in circular motion, with radius and period

$$r = \frac{mv}{Bq} \quad \text{and} \quad T = \frac{2\pi m}{qB}.$$

- Velocity selector. Suppose we have a velocity selector with a uniform magnetic field, of flux density  $B$  out of (or into) the paper. Further assume there is an electric field of strength  $E$  rightwards (or leftwards) in the selector. This is illustrated in Fig 15.7. Then, for a charged particle perpendicular to both fields to pass (undeflected) through the slits,  $F_E = F_B$ . This simplifies to

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

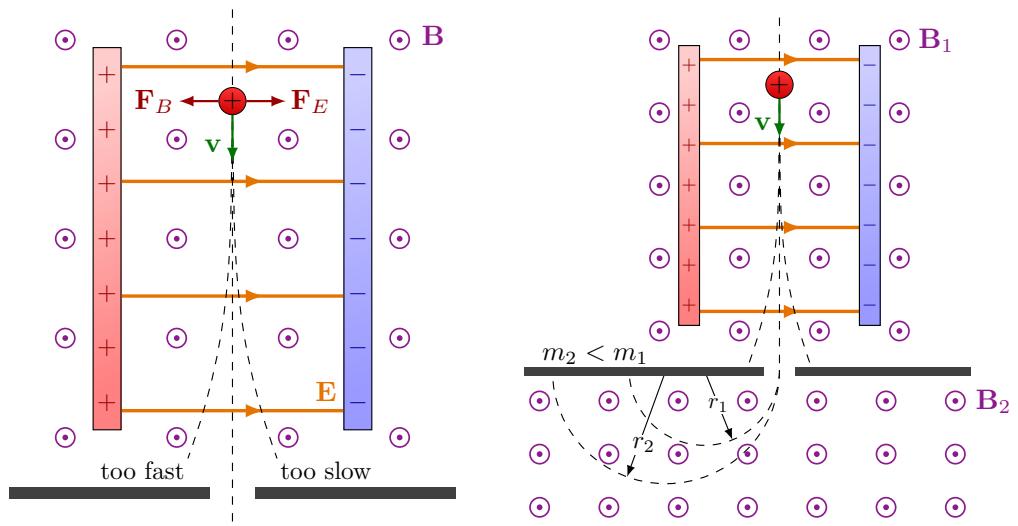


Figure 15.7: [31] An illustration of a velocity selector.

Some nice images:

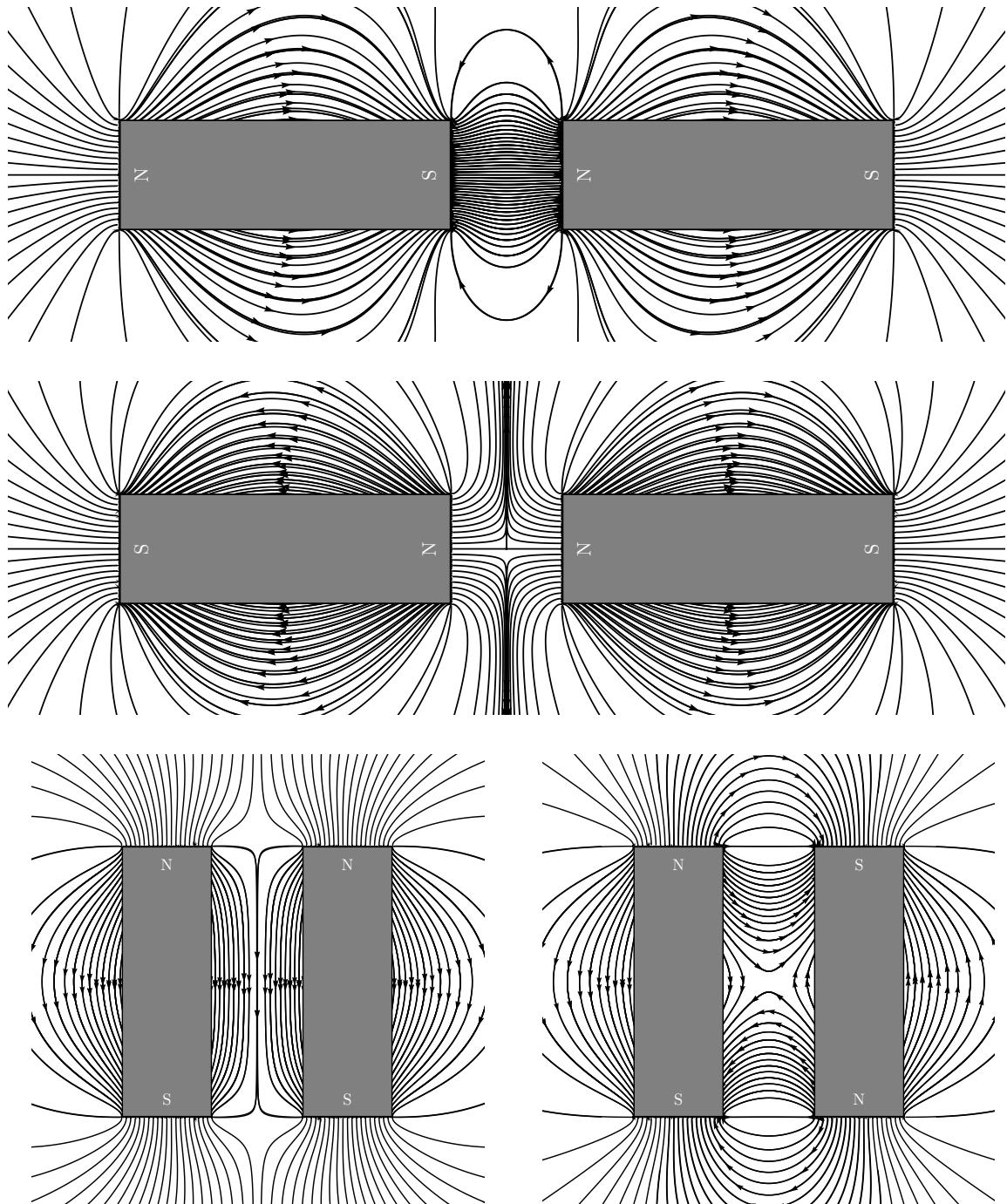


Figure 15.8: [25] Magnetic fields produced by two bar magnets.

# Electromagnetic Induction

- Magnetic flux is the product of an area and the component of magnetic flux density perpendicular to that area.
- In other words, let  $A$  be an area in a uniform magnetic field, of flux density  $B_{\perp}$  perpendicular to  $A$ . Then, the magnetic flux  $\Phi$  through  $A$  is

$$\Phi = B_{\perp}A.$$

- The area  $A$  here is a *vector*! When we flip it through  $\pi$  radians, the magnetic flux through it is now  $-\Phi = -B_{\perp}A$ .
- One weber is the *magnitude* of magnetic flux through an *area* of  $1m^2$  when a *magnetic field* of  $1T$  acts *perpendicularly into* the area.
- Magnetic flux linkage through a coil is defined as the *product* of the *number of turns* of the coil and the magnetic flux through each turn of the coil.
- The magnetic flux through a coil of  $N$  turns is hence

$$N\Phi = NB_{\perp}A.$$

- Faraday's Law of Electromagnetic Induction states that the *e.m.f.* induced in a conductor is *directly proportional to the rate of change of magnetic flux linkage*.
- Lenz's Law states that the *direction* of the induced *e.m.f.* is such that it may produce *an effect* that *opposes the change* causing it.
- Lenz's Law is a consequence of conservation of energy. Mechanical work done to enable the change in magnetic flux linkage is converted into electrical energy.
- Faraday's and Lenz's Laws imply that the *e.m.f.* generated is

$$E = -(N\Phi)' = -(NB_{\perp}A)'.$$

(The negative sign indicates that the induced *e.m.f.* opposes the change in magnetic flux linkage.)

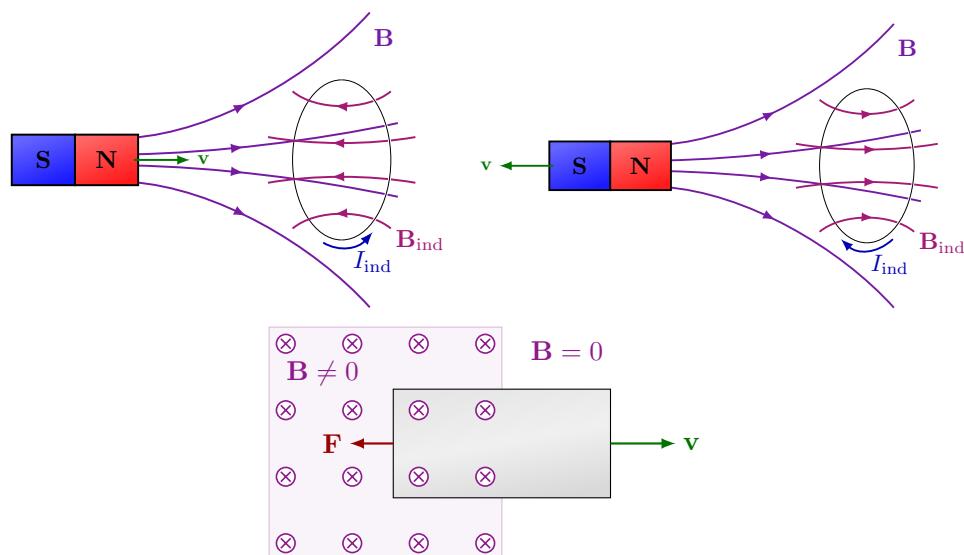


Figure 16.1: [32] Examples of Lenz's Law in action.

- Motional e.m.f.: Suppose we have a circuit as shown in the bottom left of the following figure. Then, by Faraday's Law,

$$|E| = \Phi' = B(\Delta A) = Blv.$$

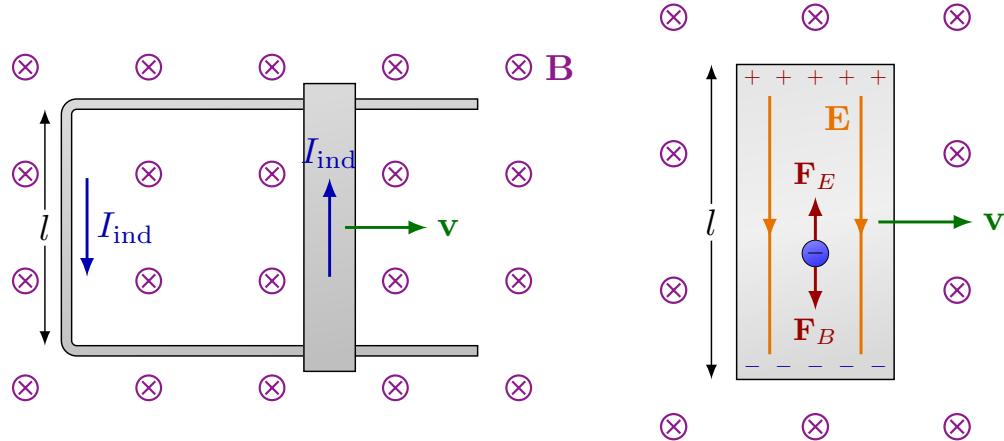


Figure 16.2: [32] Example of motional emf.

- Conventions for polarity and when to use them.

| Energy conversion    | Function in a circuit | Convention for polarity                |
|----------------------|-----------------------|--|
| Electrical to others | Resistor/Wire         | Higher potential = relatively positive |
| Others to electrical | Battery               | Lower potential = relatively positive  |

- Faraday's Paradox. Consider a metal disc with area  $A$  rotating at frequency  $f$  in a uniform magnetic field, of flux density  $B$ . Then, let  $O$  be the centre of the disk, and pick any point  $P$  along the circumference of the disk. We see that  $A'$ , the area swept by  $OP$  per unit time, is  $\pi r^2 f$ . So, by Faraday's Law,

$$E = B\pi r^2 f.$$

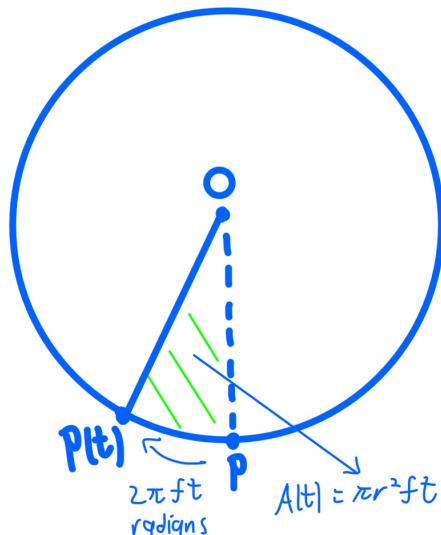


Figure 16.3: [18] An illustration of Faraday's Paradox.

# Alternating Current

- An *alternating current (a.c.) source* creates an electrical *current* that varies in magnitude *and direction periodically with time*, as opposed to a *direct current (d.c.) source* where the *direction of the current stays constant*.
- Alternating current *must change direction*. For instance, the following two functions, namely  $I = \sin(t) + 1$  and  $I = \cos(t) + 1$ , are both (varying) direct currents.

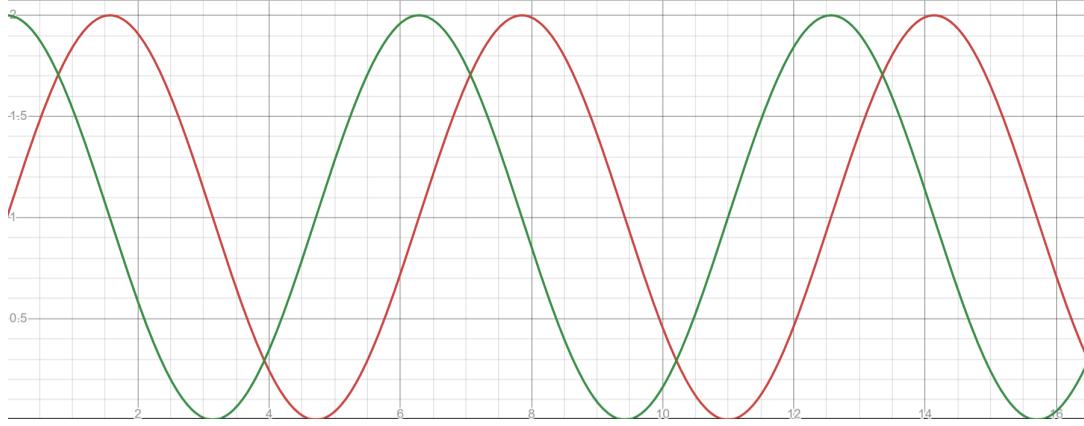


Figure 17.1: [33] Direct currents.

- A  $kV f$  Hz a.c. supply is one which has  $V_{\text{rms}} = k$  and frequency  $f$ .
- The *root-mean-square (r.m.s.)* value  $I_{\text{rms}}$  (or  $V_{\text{rms}}$ ) of an *alternating current* (or alternating voltage) is the value of a *steady direct current* (or direct voltage) that would produce the *same average power* in a given resistor.
- We denote the mean value of a quantity  $x$  by  $\langle x \rangle$ . So,  $x_{\text{rms}} = \sqrt{\langle x^2 \rangle}$ , and it also holds that

$$\langle P \rangle = I_{\text{rms}}^2 R = \frac{V_{\text{rms}}^2}{R}.$$

- Steps to determine the rms value: square → mean → root.
  1. Square all values of  $I$  (or  $V$ ).
  2. Find the mean square value  $\langle I^2 \rangle$  (or  $\langle V^2 \rangle$ ). This is just the area under the graph of  $I^2$  (or  $V^2$ ) against  $t$  in one period.
  3. Square root the value obtained above.
- Note that for a *full wave sinusoidal* alternating current (which can be assumed unless otherwise stated),

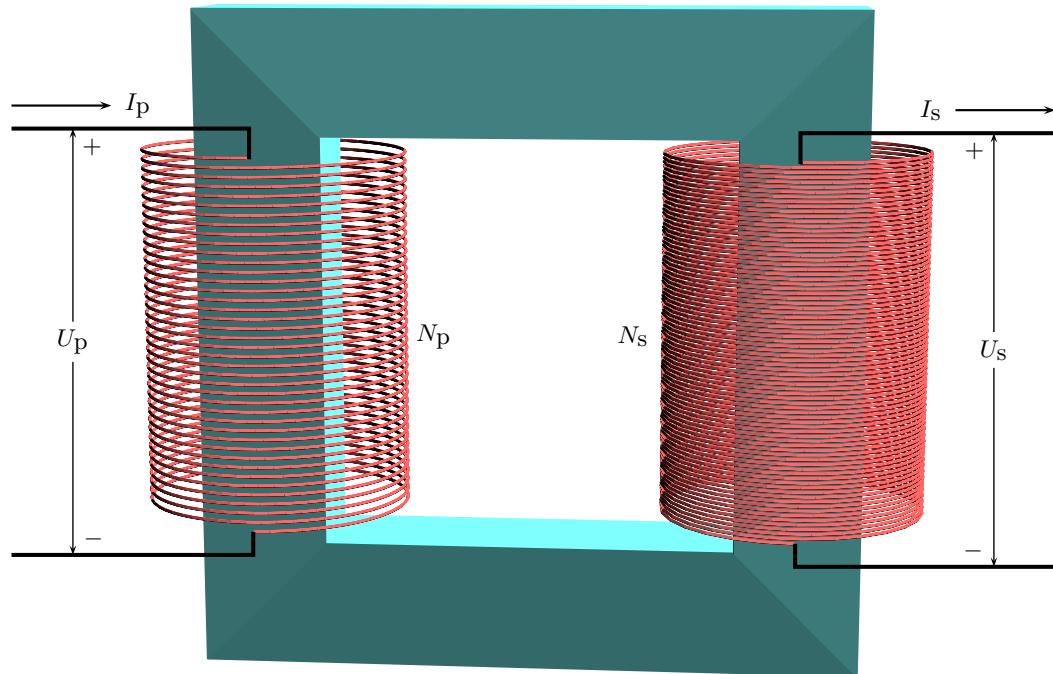
$$\langle P \rangle = \frac{1}{2} P_0, \quad V_{\text{rms}} = \frac{1}{\sqrt{2}} V_0, \quad \text{and} \quad I_{\text{rms}} = \frac{1}{\sqrt{2}} I_0.$$

- Transformers. Let  $N_P$ ,  $V_P$ , and  $I_P$  be the number of turns, voltage, and current, respectively, in the primary winding. Similarly define  $N_S$ ,  $V_S$ , and  $I_S$  for the secondary winding. Then,

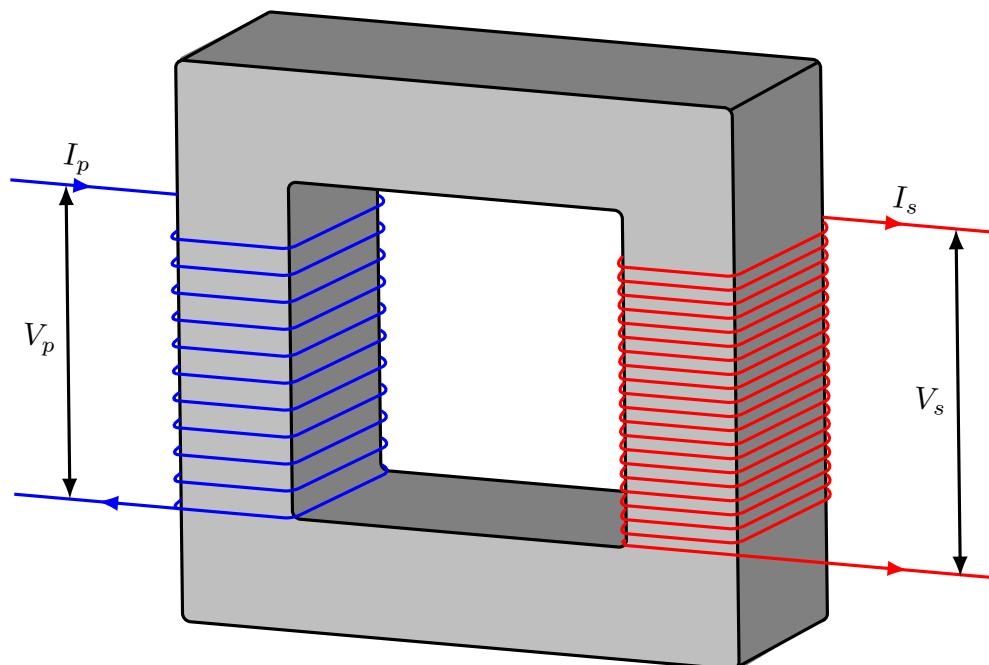
$$\text{the turns ratio} := \frac{N_S}{N_P} = \frac{V_S}{V_P} = \frac{I_P}{I_S}.$$

(To quickly determine which side carries a greater voltage, we can use the principle of ‘more turns, more voltage’.)

- A step up transformer is one that increases voltage, i.e.  $V_S > V_P$  (or  $N_S > N_P$ ).
- A step down transformer is one that decreases voltage, i.e.  $V_P > V_S$  (or  $N_P > N_S$ ).

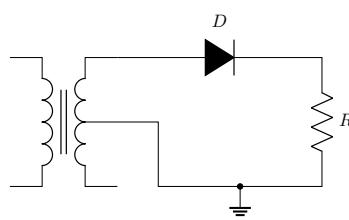


**Figure 17.2:** [34] A step-up transformer with  $N_P = 40$  and  $N_S = 80$ .

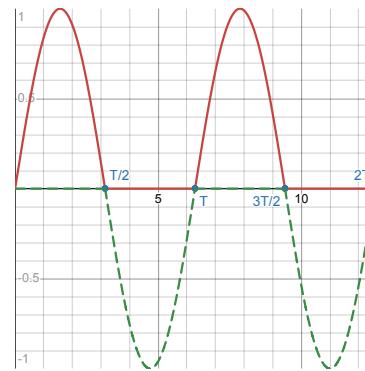


**Figure 17.3:** [35] Another step-up transformer.

- Transformers cannot be used for *constant* direct current. Since there is no change in voltage/current, no emf will be (constantly) induced in the secondary coil.
- When the direct current varies, however, there will be an *alternating* current induced.
- Energy loss in a transformer.
  1. Winding resistance. Current flowing through the windings causes *resistive heating* of the conductors.
  2. Hysteresis losses. Each time the *magnetic field is reversed*, a small amount of energy is lost due to hysteresis within the core.
  3. Magnetostriction. Magnetic flux in a ferromagnetic core causes it to physically expand and contract slightly with each cycle of the magnetic field. This produces a *buzzing sound* and can cause losses due to *frictional heating*.
  4. Mechanical losses. The alternating magnetic field causes fluctuating forces between the primary and secondary windings. These cause vibrations within nearby metalwork, adding to the *buzzing noise* and *consuming a small amount of power*.
- Power is typically transmitted at high voltages to minimise the power lost during transmission.
- Rectification.
  - A *half-wave rectification* converts only *half* of the a.c. into d.c. by allowing current flow in only one direction.

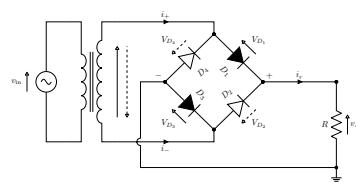


(a) [36] Circuit diagram.

(b) [37] The red and green lines denote the  $V_R - t$  and  $V_D - t$  graphs, respectively.**Figure 17.4:** Half-wave rectification.

- \* First half cycle ('positive' V and I)
  - The diode is *forward-biased* and has almost zero resistance, allowing the flow of current through the circuit.
  - There is negligible p.d. (approximately zero) across the diode due to the low resistance.
  - Thus, p.d.  $V_R$  across the resistor R is equal to the a.c. input voltage.
  - So, when the diode is forward-biased,  $V_R$  follows the a.c. supply.
- \* Latter half cycle ('negative' V and I)
  - The diode is now *reverse-biased* and has almost infinite resistance, such that only a negligible current flows through it.

- The p.d. across the diode is equal to the a.c. input supply voltage as its resistance is very much larger than  $R$ .
- Thus, the p.d.  $V_R$  across  $R$  is negligible.
- So, when the diode is reverse-biased,  $V_R = 0$ .
- A *full-wave rectification* converts *all* of the a.c. into d.c. by inverting the negative current flow into positive current flow.



(a) [38] Circuit diagram.

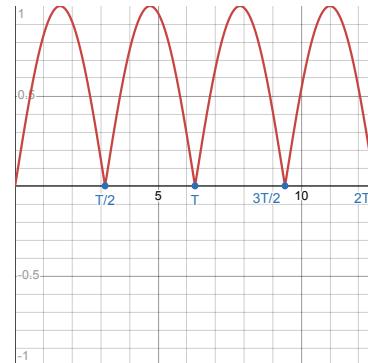
(b) [39] The  $V_R - t$  graph.

Figure 17.5: Full-wave rectification.

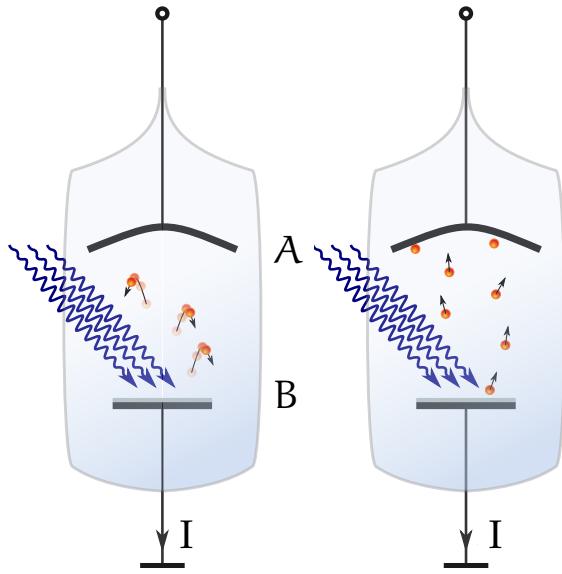
# Quantum Physics

- \* A photon is defined as a quantum of electromagnetic energy.
- The energy of a photon is given by  $E = hf = hc/\lambda$ , where Planck's constant  $h = 6.63 \cdot 10^{-34}$  Js. A useful conversion:  $1 \text{ eV} = 1.60 \cdot 10^{-19} \text{ J}$
- \* The photoelectric effect refers to the emission of electrons from a metal surface when the surface is irradiated with electromagnetic radiation of a high enough frequency.

| Experimental observations  | Predictions of classical theory   | Explanation via quantum theory   |
|--|---|--|
| <ul style="list-style-type: none"> <li>• Emission of photoelectrons is almost instantaneous, with a negligible time lag.</li> <li>• Is unaffected by the intensity or brightness of the light if the light is above the threshold frequency.</li> </ul>  | <ul style="list-style-type: none"> <li>• Electrons should absorb energy over a period of time before it gains enough energy to escape the metal.</li> <li>• A dim light after some delay would transfer sufficient energy to the electron for ejection, whereas a very bright light would eject electrons after a short while.</li> </ul> | <ul style="list-style-type: none"> <li>• Photon-electron interaction is one-to-one.</li> <li>• Energy of a single photon cannot be shared; it either gives up all of its energy to the electron, or none at all.</li> <li>• This absorption of the photon then leads to a gain in energy for the electron.</li> <li>• The time taken for the electron to gain sufficient energy is negligible. Hence, photoemission is instantaneous.</li> </ul> |
| <ul style="list-style-type: none"> <li>• Electrons are emitted when the frequency of light is above the threshold frequency <math>f_0</math> (or below the threshold wavelength <math>\lambda_0</math>).</li> <li>• No electron is emitted below <math>f_0</math>, regardless of the light intensity.</li> </ul> | <ul style="list-style-type: none"> <li>• Energy of the wave is dependent on the square of its amplitude.</li> <li>• Electrons will absorb enough energy to escape given sufficient time.</li> <li>• There should not be any threshold frequency.</li> </ul>   | <ul style="list-style-type: none"> <li>• The existence of the threshold frequency again traces back to the one-to-one interactions between electrons and photons.</li> <li>* The work function <math>\phi</math> is the minimum energy required to eject/free an electron from the surface of a metal.</li> <li>• Note. The energy <math>E \geq \phi</math> required to free an electron varies from electron to electron.</li> </ul>            |

|  |  |   |   |
|--|--|---|---|
| <p>The <i>maximum kinetic energy</i> of the ejected electrons is independent of the <i>intensity</i> of the light, but dependent on the <i>frequency</i> of the light.</p> | <p>The higher the light <i>intensity</i>, the higher the <i>energy</i> of the light wave striking the metal surface. Electrons should be ejected with <i>greater</i> kinetic energy. It <i>cannot</i> explain why the maximum kinetic energy is dependent on frequency and independent of intensity.</p> | ✗ | <ul style="list-style-type: none"> <li>By the conservation of energy, energy imparted by a photon is used to <i>free</i> the electron and becomes the <i>kinetic energy</i> of the emitted electron.</li> <li>For an electron requiring the <i>minimum</i> energy <math>\phi</math> to escape from the metal, its kinetic energy will be a <i>maximum</i>. i.e. <math>hf = \phi + E_{k,\max}</math>.</li> <li>When the light source increases in <i>frequency</i>, the <i>energy</i> <math>E_{\text{photon}} \propto f</math> of the emitted <i>photons</i> increases proportionately. So, the <i>maximum</i> kinetic energy <math>E_{k,\max} = E_{\text{photon}} - \phi</math> of the electrons emitted also increases.</li> </ul> |
| <p>The <i>rate</i> at which electrons were ejected, and therefore, the <i>photocurrent</i> produced is proportional to the <i>intensity</i> of the light.</p>              | <p>A higher light intensity should be able to simultaneously free more electrons from the metal at any instant. This results in a higher current.</p>  | ✓ | <p>The <i>intensity</i> of the <i>monochromatic</i> light beam is directly proportional to the number of <i>photons</i> passing through a cross-sectional <i>area</i> per unit <i>time</i>. In fact,</p> $I = \frac{N}{t} \cdot \frac{hf}{A} = \frac{Nhf}{tA}.$ <p>The higher the light <i>intensity</i>, the higher the <i>number of photons per unit time</i> hitting the metal surface, and hence, its electrons.</p>  |

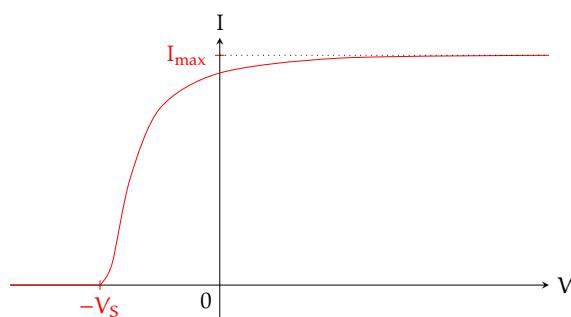
**Table 18.1:** The photoelectric effect, in summary.



**Figure 18.1:** [43] An illustration of the photoelectric effect.

- A is negative relative to B ( $V = V_A - V_B < 0$ ).
  - Electrons decelerate when moving towards A.
  - If the kinetic energy  $E_k$  of an electron exceeds  $eV$ , then it will reach electrode A.
  - And when  $E_k < eV$ , the electron will be repelled back to electrode A.
  - As  $V$  increases, more electrons have insufficient  $E_k$  to reach electrode A. i.e., less electrons reach A. So, the photocurrent is reduced.
  - At the stopping potential  $V_s$ , even the most energetic electrons have insufficient  $E_k$  to reach A. i.e.  $eV_s = E_{k,\max}$ . Hence, there is no photocurrent.

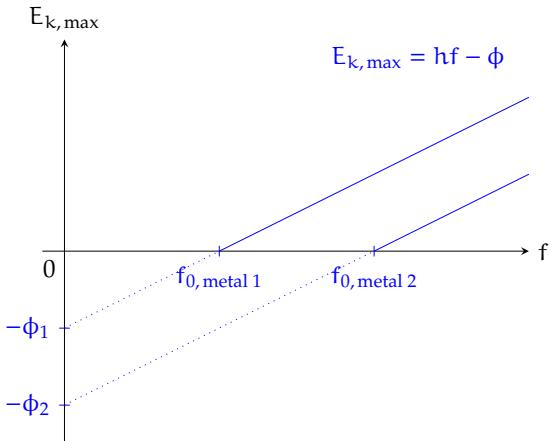
- A is positive relative to B ( $V = V_A - V_B > 0$ ).
  - All electrons accelerate towards A.
  - The saturation current is not immediately reached because some electrons' path are such that they do not hit electrode A. So, a sufficiently strong electric field is required for them to hit A.



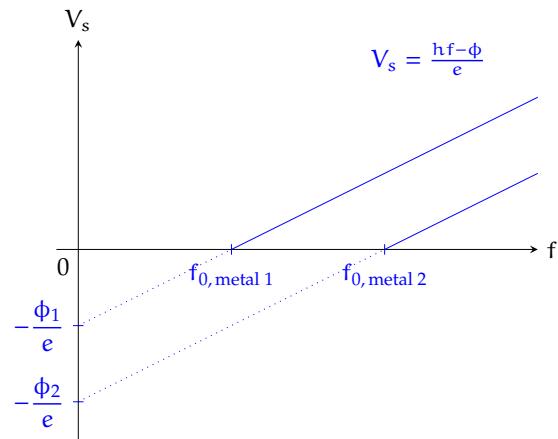
**Figure 18.2:** [44] An illustration of the photoelectric effect.

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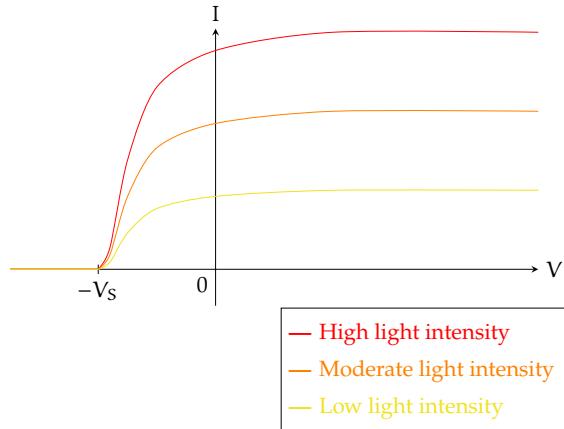
<sup>o</sup>Totally didn't take me 5-7 hours to tex out the next page... Tikz is pain, suffering, but beautiful.



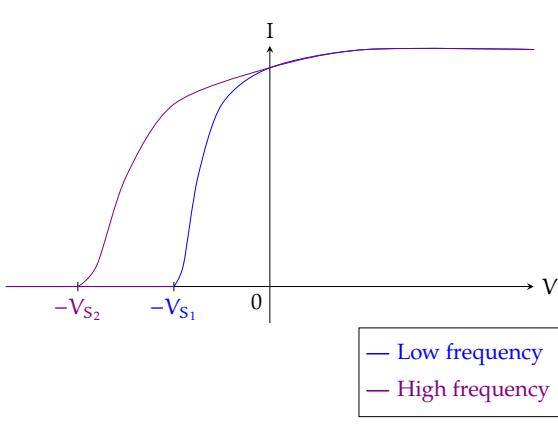
(a) The maximum kinetic energy of a photoelectron plotted against the frequency of light used.



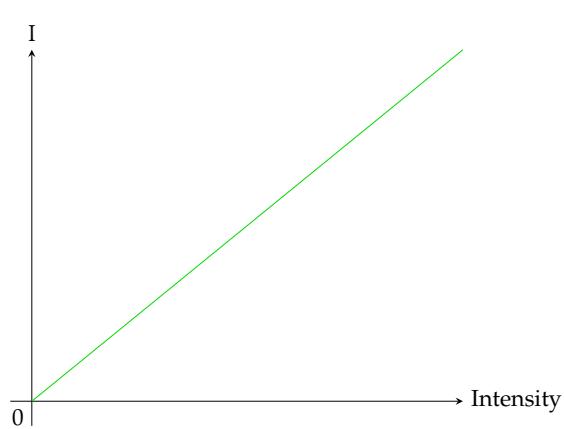
(b) The stopping potential for a metal surface plotted against the frequency of light used.



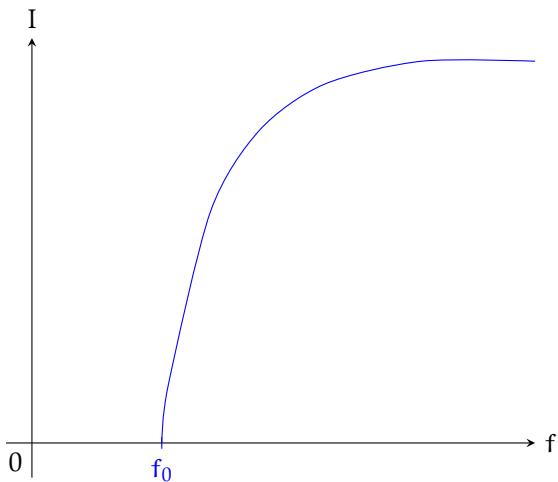
(c) The graph of photocurrent  $I$  against potential difference  $V = V_A - V_B$ , under (a constant frequency but) varying intensities of light.



(d) The graph of photocurrent  $I$  against potential difference  $V = V_A - V_B$ , under (a constant rate of photon emission but) varying frequencies of light.



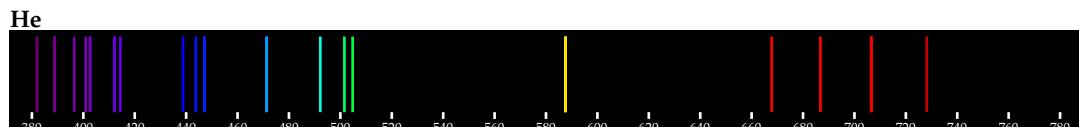
(e) The graph of photocurrent  $I$  against the intensity of light used (under a constant frequency, which exceeds the threshold).



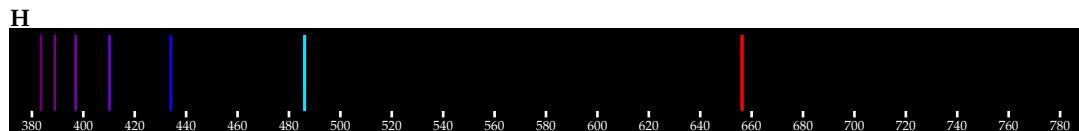
(f) The graph of photocurrent  $I$  against the frequency of light used (under a constant rate of photon emission).

**Figure 18.3:** [44] The photoelectric effect: the relationship between the maximum kinetic energy  $E_{k,\max}$ , the stopping potential  $V_s$ , photocurrent  $I$ , potential difference  $V = V_A - V_B$ , frequency  $f$  of light used, intensity of light used.

- The *de Broglie wavelength* of any particle is given by  $\lambda = h/p$ .
  - The Heisenberg Uncertainty Principle states that  $\Delta p \Delta x \gtrsim h$ , where  $p$  and  $x$  are the momentum and position, respectively, of a particle.
  - Note. The above applies only when considering the momentum  $p$  and position  $x$  *in the same direction*. So, it is possible that, for example,  $\Delta x \Delta p_y = 0$  or  $\Delta y \Delta p_x = 0$ .
  - The energy of a photon involved in the transition between energy levels obeys energy conservation. i.e.  $hf = E_f - E_i$  where  $f$  is the photon's frequency.
  - Some terminology.
    1. The *ground state* of an atom is the lowest state an atom can be at, such that all electrons in the atom occupy the lowest possible energy levels.
    2. An atom is said to be *excited* iff one or more of its electrons are not occupying the lowest possible energy states.
    3. For this topic, *ionisation* is the removal of an electron to create an ion.
    4. The *ionisation energy* of an atom is the energy required for the atom to transition from the  $n = 1$  to  $n = \infty$  state.
- \* An *emission line spectrum* is a series of distinctly coloured lines against a dark background.



(a) The emission line spectrum of Helium.



(b) The emission line spectrum of Hydrogen.

Figure 18.4: [47] Some emission line spectra.

- Excited atoms are unstable and de-excite by *emitting* photons, eventually reaching the ground state (it does not have to immediately de-excite to the ground state).
- The frequency of these photons is such that  $hf = E_i - E_f$ , where  $E_i$  and  $E_f$  are the initial and final energy states, respectively ( $f$  can be nonzero).
- Each emission spectrum is unique to each element.
- Given  $n$  energy states, there will be  $(n)_2$  emission lines.

\* An *absorption line spectrum* is a series of distinct dark lines against a continuous spectrum.

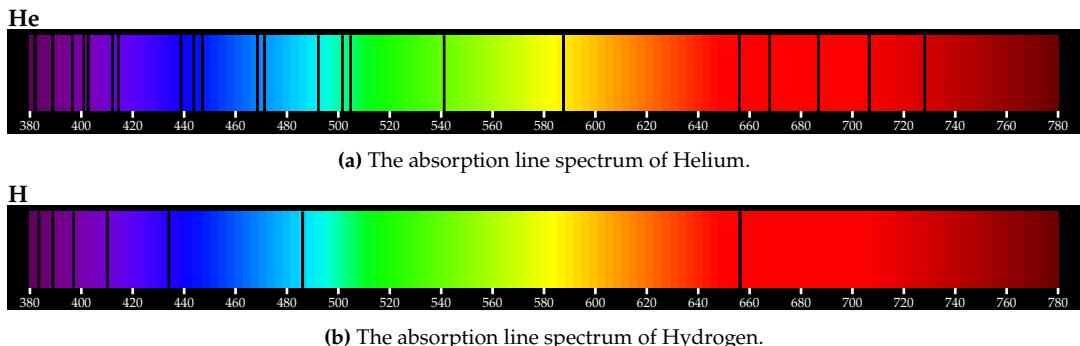


Figure 18.5: [47] Some absorption line spectra.

- Gaseous atoms *absorb* photons with (exactly) the energies they need to transit to a higher energy state, *from the ground state*. (We do not consider further excitations from above a higher energy level.)
- Given  $n$  energy states, there will be  $n - 1$  absorption lines.
- If an element  ${}^A_Z X$  lies on the  $m$ th row and in the  $n$ th group of the periodic table, then an atom of  $X$  at ground state has  $m$  electron shells and  $n$  valence electrons.
- The maximum number of electrons that can occupy the  $n$ th shell of an atom is  $2n^2$ .

| Shell  |        | Maximum number of electrons |
|--------|--------|-----------------------------|
| Number | Letter |                             |
| 1st    | K      | 2                           |
| 2nd    | L      | 8                           |
| 3rd    | M      | 18                          |
| 4th    | N      | 32                          |

Table 18.2: The maximum number of electrons that can occupy the first four shells of an atom.

- Similarity: All distinct lines in an absorption line spectrum are present and of the *same wavelengths* in an emission line spectrum for the same atoms.
- Difference: There are at least as many emission lines as there are absorption lines. In general, there are *more* emission lines.
- Note. It is critical to accurately represent the distance between the each emission line (or absorption line), especially the one furthest away from adjacent lines. E.g. the line near the 660 nm mark in Figure 18.4b or 18.5b.

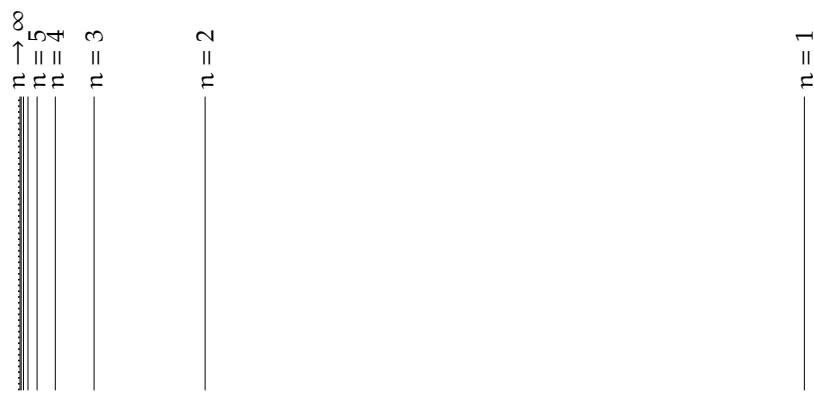
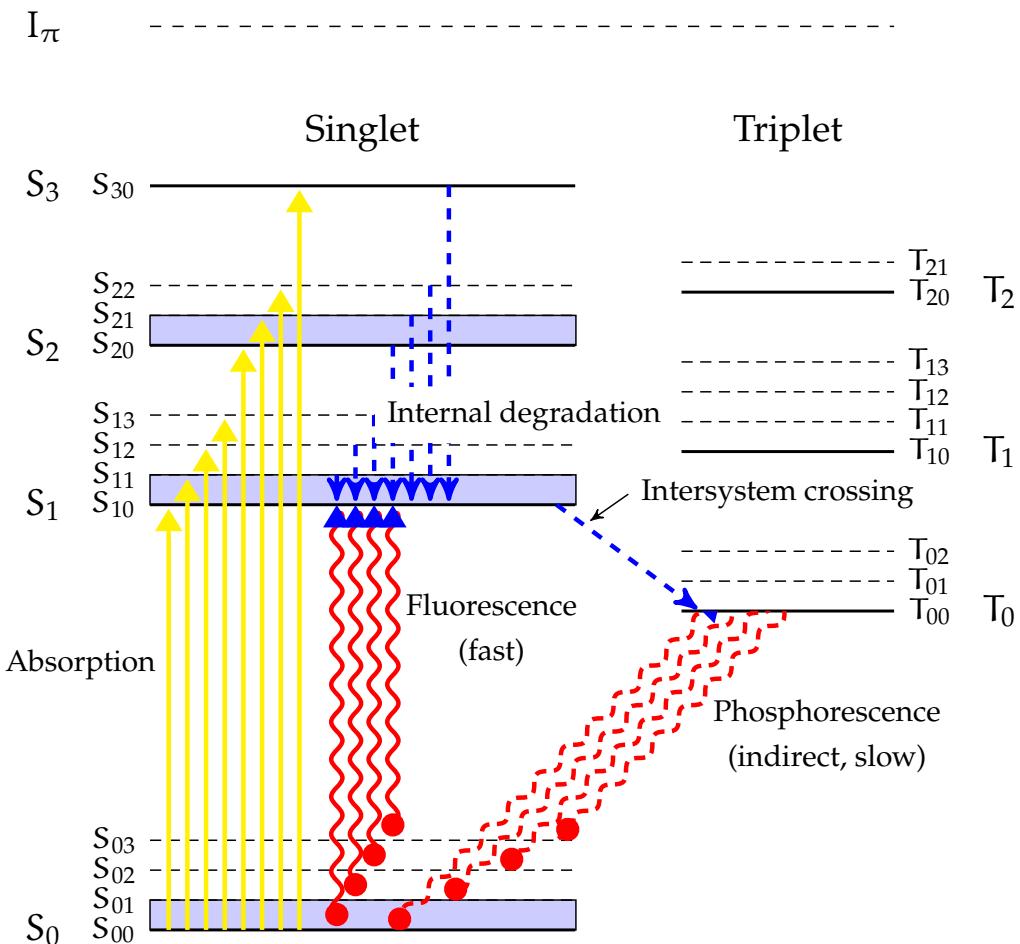
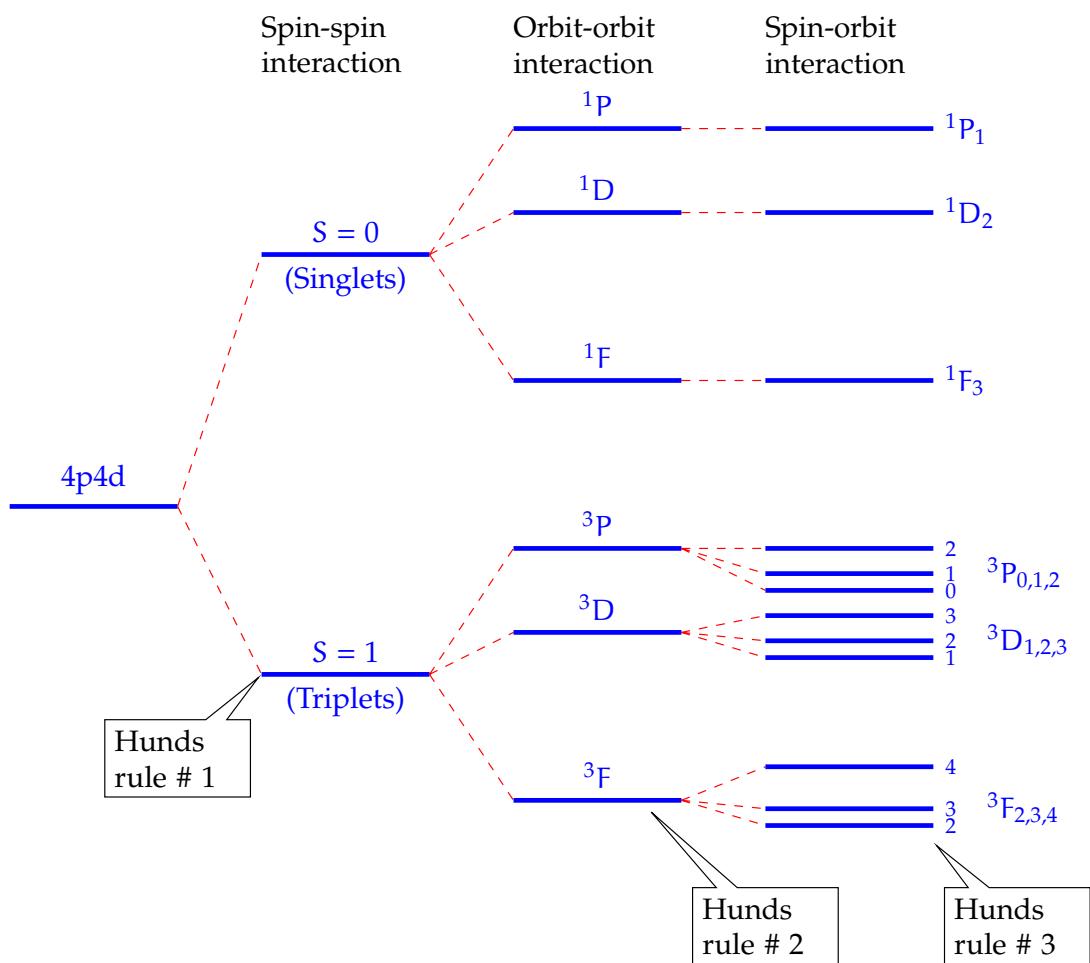


Figure 18.6: [48] The energy levels of Hydrogen (drawn to scale).



**Figure 18.7:** [45] (Pretty diagram; *out of syllabus*) Typical energy levels for  $\pi$ -orbitals of a fluor molecule. Spin singlet ( $S$ ) and triplet ( $T$ ) states are separated for clarity. The ionization level  $I_\pi$  is shown at the top. Excited states as well as vibrational sublevels (dashed horizontal lines) are shown. Internal degradation is a non-radiative process, while fluorescence and phosphorescence are radiative decays. The decay  $T_0 \rightarrow S_0$ , however, is indirect, by interactions with other molecules.



**Figure 18.8:** [46] (Another pretty diagram; *out of syllabus*) An illustration of Hund's rule.

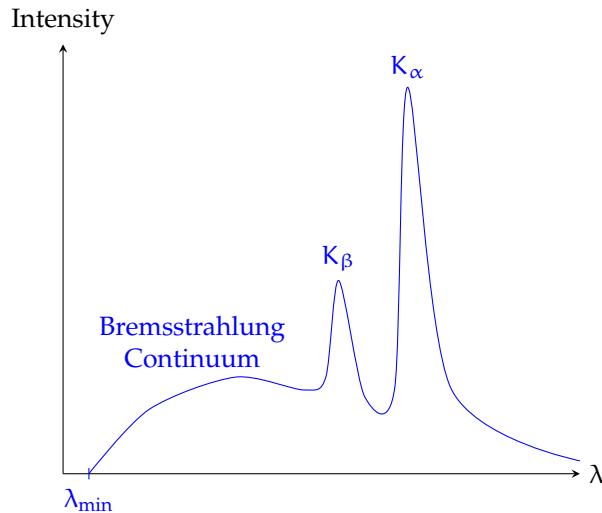


Figure 18.9: [49] X-ray spectrum.

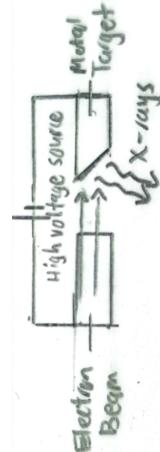


Figure 18.10: [50] Experimental set-up to produce X-rays

| Features  | Explanation  |
|---|--|
| A sharp cut-off / minimum wavelength $\lambda_{\min}$   | <ul style="list-style-type: none"> <li>Incident electrons are accelerated through an electric potential <math>V</math>, giving them a maximum kinetic energy of <math>E_k = eV</math>.</li> <li>When such an electron is decelerated and loses all its <math>E_k</math>, it emits a single X-ray photon of maximum possible energy, corresponding to the minimum wavelength seen on the spectrum.</li> <li>By the conservation of energy, <math>eV = \frac{hc}{\lambda_{\min}}</math> so <math>\lambda_{\min} = \frac{hc}{eV}</math>.</li> </ul> |
| A broad continuous spectrum known as the <i>Bremsstrahlung continuum</i> . (Bremsstrahlung is braking radiation in German.) | <ul style="list-style-type: none"> <li>When incident electrons pass by the nucleus, they are accelerated.</li> <li>Their kinetic energies are lost through the emission of Bremsstrahlung.</li> <li>Since the magnitude of the acceleration experienced by the incident electrons varies and is not discrete, the wavelengths of the emitted photons have a continuous distribution.</li> <li>Hence, the Bremsstrahlung produces a continuous spectrum of electromagnetic radiation.</li> </ul>  |

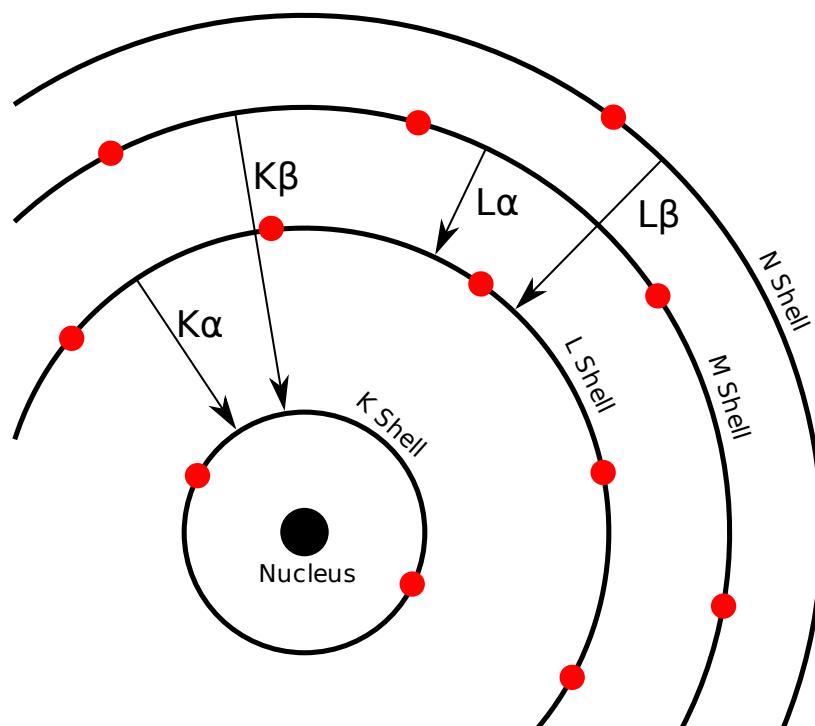
- An accelerated incident electron ‘collides’ with an electron from the innermost K-shell, kicking it out of the shell.
- The atom is excited due to the vacancy in the K-shell.
- An electron from the higher energy shell transits to the K-shell, emitting a photon.

Sharp peaks  $K_{\alpha}$  and  $K_{\beta}$  called characteristic lines/X-rays.

|   | Series   | Line         | Initial shell (m) | Final shell (n) | $m - n$ |
|---|----------|--------------|-------------------|-----------------|---------|
| • | K series | $K_{\alpha}$ | L-shell (2nd)     | K-shell (1st)   | 1       |
|   |          | $K_{\beta}$  | M-shell (3rd)     |                 | 2       |
|   | L series | $L_{\alpha}$ | M-shell (3rd)     | L-shell (2nd)   | 1       |
|   |          | $L_{\beta}$  | N-shell (4th)     |                 | 2       |

- See Figure 18.11 for an illustration.
- Every element has a unique set of energy levels, and hence, characteristic lines.

**Table 18.3:** The features of an X-ray spectrum.



**Figure 18.11:** [51] X-ray series

# Nuclear Physics

- The Rutherford-Geiger-Marsden experiment.

| Observation  | Explanation  |
|--|--|
| Most $\alpha$ -particles passed straight through the foil, <i>undeflected</i> .  | The nucleus is <i>very small</i> in size compared to the atom as a whole, which mostly comprises of <i>empty space</i> . |
| Less than <b>1%</b> of the $\alpha$ -particles were <i>scattered backwards</i> , with an angle of <i>deflection</i> exceeding $90^\circ$ . | Most of the mass of an atom is <i>concentrated</i> in a <i>very small positively charged region</i> .                    |

**Table 19.1:** The Rutherford-Geiger-Marsden experiment: observations and explanations.

- \* A *isotope* is one of two or more atoms with the *same atomic number* but *different number of neutrons*.
- \* The *unified atomic mass unit u* is equivalent to *one-twelfth* of the mass of a carbon-12 atom. i.e.  $1 \text{ u} = 1.66 \cdot 10^{-27} \text{ kg}$ .
- \* The *mass defect* is the amount by which the mass of an atomic *nucleus* is less than the sum of the masses of its *constituent particles*. i.e.

$$\text{mass defect } \Delta m = \text{sum of masses of nucleons} - \text{mass of nucleus.}$$

- \* The *binding energy* of a nucleus is the amount of energy that is required to *break a nucleus* into its *constituent nucleons*.
- Binding energy is not a form of stored energy.
- Mass-energy equivalence:  $E = mc^2$ .
- \* The *binding energy per nucleon* is defined as the *binding energy* of a nucleus divided by the *number of nucleons* in the nucleus.

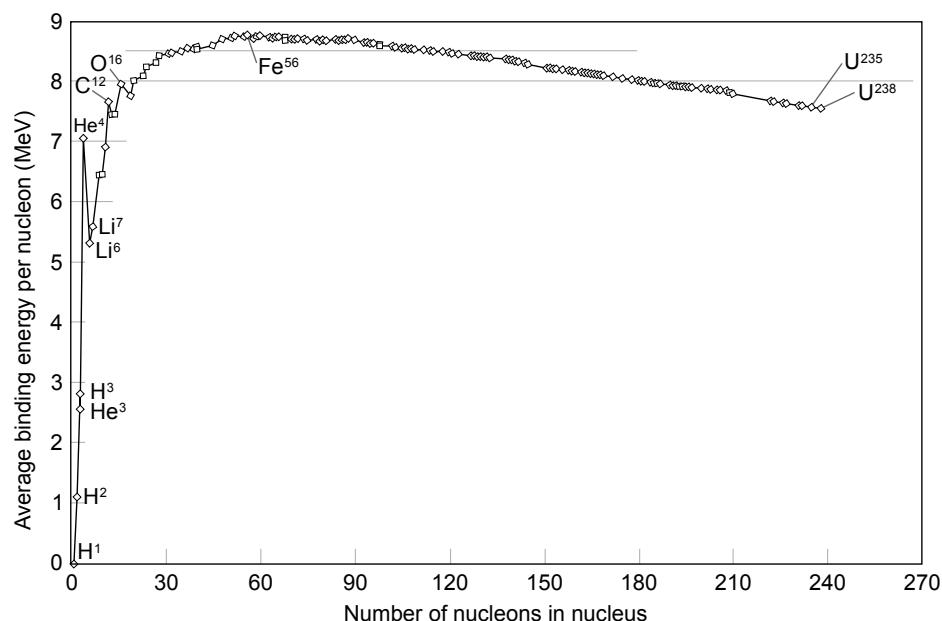
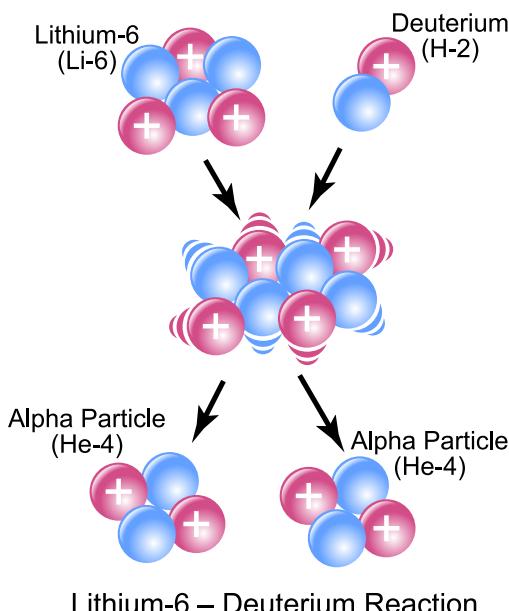


Figure 19.1: [40] The variation of binding energy per nucleon with nucleon number.

- Remember that, Fe-56 has a binding energy per nucleon of 8.8 MeV and is located near (slightly to the right) of the peak.
- The binding energy per nucleon can be seen as a measure of stability: a higher binding energy per nucleon corresponds to a higher stability of the nucleus.



- Nuclear fusion is the process where light nuclei fuse into a heavier nucleus that is more stable. Energy is liberated.
- Nuclear fission is the process where a heavy nucleus splits into two lighter nuclei that is more stable. Energy is liberated.
- Useful equations for calculating the energy liberated in a nuclear reaction.
  1.  $\text{energy released} = (\text{mass of reactants} - \text{mass of products})c^2$ .
  2.  $\text{energy released} = \text{B.E. of products} - \text{B.E. of reactants}$ .
- Conserved quantities in nuclear reactions.
  1. Nucleon number.
  2. Charge. The *atomic numbers* of reactants and products each sum to the same total. *But*, the total *number of protons* may change due to beta decay. i.e.  ${}^A_Z X \rightarrow {}^A_{Z+1} X + {}^0_{-1} e$ .
  3. Mass-energy.

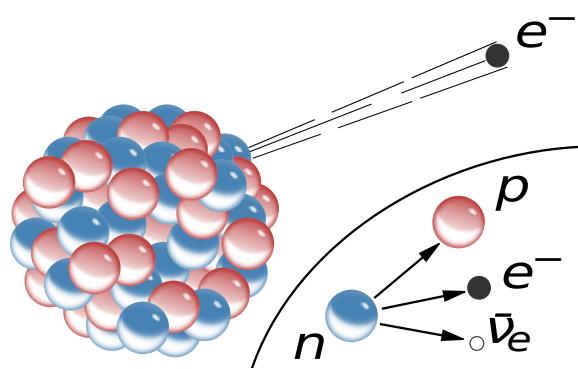
Figure 19.2: [41] Nuclear fusion followed by fission.

\* Radioactive decay is *spontaneous* and *random*.

- *Spontaneous* means that the nucleus decays because it is *unstable*, not because of *external conditions*.
  - Random means that it is impossible to predict *which* nucleus will delay or *when* a particular nucleus will decay.
- \* *Background radiation* is the radiation detected by a *radiation counter* when *no radioactive source* is nearby.
- \* The *activity A* of a radioactive isotope is defined as the number of *nuclear disintegrations per unit time*.
- The count rate C is the rate at which counts are triggered on a ratemeter, by ionising radiation.
  - Note. The count rate is *not the same* as activity. In fact,  $C \leq A$  because not all emissions — stemming from radioactive decay — are counted. Some reasons include:
    1. Not all the radiation is directed towards the detector.
    2. Some of the radiation will be absorbed in the source itself, and by the air between the source and the detector.
- \* The *decay constant λ* of a *sample of a radioactive nuclide* is the *probability* that a nucleus will *decay per unit time*.
- The number N of undecayed nuclei is such that  $A = -\frac{dN}{dt} = \lambda N$ .
  - The number N of undecayed nuclei, mass m of radioactive sample, activity A, and count rate C all follow the equation  $y = y_0 e^{-\lambda t}$  ( $y = N, m, A, C$ ).
- \* The *half-life  $t_{1/2}$*  of a *radioactive isotope* is the *average time* taken for its *activity to be halved*. Note.  $\lambda t_{1/2} = \ln(2)$ .

| Type of decay | Equation   | Ionising power ↓                | Penetration power ↑                 | Velocity  |
|---------------|--|---------------------------------|-------------------------------------|---|
| Alpha decay   | $\alpha\text{-particle (zero electrons)}$<br>${}^A_Z X \rightarrow {}^{A-4}_{Z-2} Y + {}^4_2 He$ | Strong<br>( $10^5$ ions per cm) | Stopped by a few cm of air or paper | $10^7 \text{ ms}^{-1}$ or $0.1c$                        |
| Beta decay    | $\beta\text{-particle}$<br>${}^A_Z X \rightarrow {}^A_{Z+1} Y + {}^0_{-1} e$                     | ( $10^3$ ions per cm)           | 5 mm of aluminum                    | Continuous range up to $10^8 \text{ ms}^{-1}$ or $0.9c$ |
| Gamma decay   | $\gamma\text{-ray}$<br>$\text{---} \rightarrow \text{---} + {}^0_0 \gamma$                       | Weak<br>(indirect ionisation)   | Several cm of lead                  | c   |

Table 19.2: Types of radioactive decay.



**Figure 19.3:** [42] Illustration of a beta decay.

- Biological effects of radiation.
  - Direct effects. When radiation interacts with DNA, affecting (or even breaking) the bonds within, it impacts the ability of a cell to reproduce and survive. Mutations may also occur, eventually leading to cancer.
  - Indirect effects. When radiation interacts with and breaks the bonds in water molecules, it creates free radicals: molecules which are highly reactive due to the presence of unpaired electrons. These free radicals form compounds which initiates harmful chemical reactions within cells, causing them to be destroyed.

- While a couple mm or cm of metal suffices to stop  $\beta$ -particles, X-rays (bremsstrahlung) may be produced outside the container. So, thicker layers of lower atomic mass materials — plastic, wood, water, etc — may be preferable.

- In a beta decay, a *neutrino* is emitted along with the  $\beta$ -particle, carrying away some kinetic energy and momentum. Hence, the electron emission may not be collinear, in the opposite direction of, the recoil of the nucleus.

# Practical

## 20.1 Measurements & Calculations

| Instrument  | Measurement       | Readings | Precision of a measurement  |         |
|---|-------------------|----------|---|---------|
| <b>Analogue Instruments</b>   | <b>in general</b> | <b>2</b> | <b>smallest division</b>  |         |
| Metre rule  | length            | 2        | 0.1 cm  | 1 mm    |
| Vernier calipers  | length            | 2        | 0.01 cm   | 0.1 mm  |
| Micrometer screw gauge  | length            | 2        | 0.001 cm  | 0.01 mm |
| Stopwatch<br>(ensure $t \geq 20$ s and<br>$\# \text{oscills} = 20 - 30$ ) | time interval     | 2        | 0.01 s<br>(but $\Delta t = 0.2 - 0.4$ s)  |         |
| Thermometer   | temperature       | 2        | 1 °C  |         |
| Voltmeter   | p.d.              | 2        | smallest division   |         |
| Ammeter   | current           | 2        | smallest division   |         |
| Protractor  | angle             | 2        | 1°  |         |
| Measuring cylinder  | volume            | 1        | 0.5 cm <sup>3</sup>   |         |
| <b>Digital instruments</b>  | <b>in general</b> | <b>1</b> | <b>smallest increment displayed</b><br>E.g. $x = 5.02$ g $\implies \Delta x = 0.01$ g |         |

Table 20.1: The precision of some standard instruments.

| Operation                                      | D.P./S.F.        |            |
|--|------------------|------------|
|  | Calculated value | Data used  |
| <b>Addition and Multiplication</b>             |                  |            |
| Addition                                       | d.p.             | least d.p. |
| Multiplication                                 | s.f.             | least s.f. |
| Multiplication by a fixed factor (e.g. $\pi$ ) | s.f.             | s.f.       |
| <b>Special Operations</b>                      |                  |            |
| Logarithms of base 10 or $e$                   | d.p.             | s.f.       |
| Trigonometric functions                        | s.f.             | s.f.       |

Table 20.2: D.P.S.F.

| Equation        | Rules  |
|-----------------|--|
| $Z = aX \pm bY$ | $\Delta Z =  a \Delta X +  b \Delta Y$                                 |
| $Z = cX^aY^b$   | $\frac{\Delta Z}{Z} =  a  \frac{\Delta X}{X} +  b  \frac{\Delta Y}{Y}$ |

Table 20.3: Uncertainty rules

- Always take the average of three measurements (and show the working for the averaging explicitly) wherever possible. This reduces the effect of random error on the value of \_\_\_, hence making it more precise.
- After finishing calculations for a question, always check whether the number of s.f. or d.p. is correct. See table 20.2.

- Note. Whenever a physical quantity is given — even a resistor clearly labelled “ $10\Omega$ ” — we still must account for its dpsf. However, if it’s the number of turns/number of oscillations/etc, do not account for its dpsf.
- Note. Even for physical constants — such as  $e = 1.90 \cdot 10^{-19}$  — their dpsf should also be taken into account! However, mathematical constants, like  $\pi$ , can be disregarded in dpsf considerations.
- Percentage uncertainty of stopwatch,

$$\frac{\Delta t}{t} = \frac{0.2}{\langle t \rangle} \cdot 100\% = \underline{\hspace{2cm}} \% \text{ (1 s.f.)}.$$

- If it’s difficult to measure a quantity accurately, we should account for it when calculating uncertainties. E.g.
  1. The base of a beaker is not flat. So its height  $h$  (measured with vernier calipers) has uncertainty  $\Delta h = 0.2 \text{ cm}$ , rather than the usual  $0.01 \text{ cm}$ .
  2. It may be difficult to precisely measure the height  $h$  of a suspended object (with a metre rule). So, we use  $\Delta h = 0.2 \text{ cm}$ , instead of the usual  $0.1 \text{ cm}$ .
  3. It is difficult to maintain protraction when measuring an angle  $\theta$  (freehand) between, say, a metre rule and a string. Therefore, we account for this by taking  $\Delta\theta = 3^\circ$ , in place of the usual  $1^\circ$ .

## 20.2 Graphing

- We should have at least six readings to plot.
- The dependent variable is always plotted as the horizontal axis.
- Always include axis labels for every big square / every  $2.0 \text{ cm}$ .
- Linearisation statement:
  - The equation can be rewritten as  $y = mx + c$ . E.g.  $\frac{1}{L} = A + Ar \cdot \frac{1}{R_2}$ .
  - Plot  $y$  against  $x$ . Then, if a straight line is obtained, the vertical intercept is  $c$  and the gradient is  $m$ .
- Draw a gradient triangle using dotted lines and label the selected points (do not mark these points out using a dot/cross/etc).
- Always check that the two points selected for calculating gradient are stated to the correct number of decimal places, corresponding to half the smallest square.

| Is there an anomalous point? | Graph  | Anomaly statement  |
|------------------------------|--|--|
| ✗                            | Do nothing.                                      | There is no anomalous point as all plotted points follow the trend of the best fit line.   |
| ✓                            | Circle the point and write “anomaly” next to it. | There is one anomalous point as it does not follow the trend of the best fit line.<br>There is one anomalous point as it lies relatively far from the best fit line, compared to other points. |

Table 20.4: Anomalous points.

### 20.3 Questions post-graphing

- State/explain whether or not the results of your experiment supports the relationship that \_\_\_\_\_.
- $$\text{Percentage difference} = \frac{k_{\text{larger}} - k_{\text{smaller}}}{k_{\text{larger}}} \cdot 100\%.$$
- Since the percentage difference of  $k = \underline{\hspace{2cm}}\% > \underline{\hspace{2cm}}\% = \underline{\hspace{2cm}}\%$  = the percentage uncertainty of  $\underline{\hspace{2cm}}$ , the results of the experiment does not support the suggested relationship.
  - Since the percentage difference of  $k = \underline{\hspace{2cm}}\% \leq \underline{\hspace{2cm}}\% = \underline{\hspace{2cm}}\%$  = the percentage uncertainty of  $\underline{\hspace{2cm}}$ , the results of the experiment supports the suggested relationship.
- Avoid writing "... because  $\underline{\hspace{2cm}}$  is not equal to  $\underline{\hspace{2cm}}$ ". Rather, we should say "... because  $\underline{\hspace{2cm}}$  is far from/near to/close to  $\underline{\hspace{2cm}}$ ".
  - NY's suggested format for writing sources of error:
    - What is error is/what causes the error,
    - Which raw data are affected.

An example. It is difficult to release the ball from the exact position (what the error is), as the ball is only released by a free hand, which is unsteady (what causes the error). This results in imprecise values of  $h$  (which raw data are affected).

- Examples of (i) significant sources of error and (ii) the ways to remedy them.

| Source of error   | Solution   |
|---|--|
| <b>RV J1 practical sessions</b>   |  |
| (J1 P01) It is difficult to maintain protraction, and hence, hard to measure $\theta$ precisely.  | Clamp the protractor using another retort stand.   |
| (J1 P04) There is significant friction between the hooks and the thread. (This adds systematic error into the measured values of $t$ .)   | Use rollers instead of hooks, to minimise the friction experienced by the moving thread.   |
| (J1 P06) The values for current and voltage constantly fluctuate throughout the experiment. This introduces significant random error, which makes the value of $c_2$ obtained less precise. | Increase the mass of the oil added into the metal significantly. (So the measured values of $t$ all increase in magnitude, reducing the effect of the random error...)   |
| (J1 P07)  | <ol style="list-style-type: none"> <li>Conduct the experiment using a sufficiently large hanger mass, such that the circular motion is more horizontal.</li> <li>Take a video of the experiment and analyse the data collected using tracking software.</li> </ol> |

|  |   |
|--|---|
| (J1 P08) It is difficult to track the oscillating mass when the amplitude of the oscillations is small and the period is short.  | <ol style="list-style-type: none"> <li>Change the two springs to one equivalent spring of similar effective spring constant.</li> <li>Use a heavier mass but which does not cause the springs to exceed their limit of proportionality.</li> <li>Provide a visual mark near the oscillating mass to help in tracking its movement.</li> </ol>                         |
| <b>RV J2 practical sessions</b>  |   |
| (J2 P04) The precise point where resonance occurs is not easily determined when the vibration of the wire is not significant enough to be observed.  | <ol style="list-style-type: none"> <li>Increase the magnetic flux density by using a stronger magnet, e.g. neodymium magnets.</li> <li>Add a white grid (e.g. graph paper) behind the wire, so that it is easier to estimate and compare the magnitude of oscillation.</li> </ol>   |
| (J2 P06) <ol style="list-style-type: none"> <li>It is hard to ensure that the oscillation is only about the vertical axis. Moreover, the ruler tends to swing back and forth, affecting the measurement of T.</li> <li>It is hard to measure the angle free-hand using a protractor without disturbing the equilibrium of the system.</li> </ol> | <ol style="list-style-type: none"> <li>Keeping the ruler in the horizontal position will make it rotate more easily about the vertical axis.</li> <li>Secure the protractor to another retort stand, so that the protractor can be brought near to the system to read off the angle.</li> </ol>   |
| <b>NY practicals</b>   |   |
| The large size of the object resulted in a larger uncertainty in the measurement.  | Use a thinner/smaller object  |
| The mark is larger than the smallest division of ____.   | Use a smaller mark.   |
| It is difficult for the naked eye to pinpoint the exact moment when the object crosses the mark.   | Take a video of the experiment. Then, using tracking software, find the exact time when the object crosses the mark.  |
| (Experiment 01) <ol style="list-style-type: none"> <li>Human reaction time.</li> <li>The rubber band is thicker than the smallest division of the ruler used and this adds error to the measured values of s.</li> </ol>   | <ol style="list-style-type: none"> <li>Place two photogates, held by retort stands, at [location of gates]. Then, connect both photogates to an electronic timer. We use this photogates set-up to start and stop the measurement of the time t.</li> <li>Replace the rubber band with a brightly coloured thin string and tie a loop around the cylinder.</li> </ol> |
| (Experiment 02) One's hand is not steady and cannot release the object from the same velocity/position consistently.   | Use a ruler/retort stand/etc to hold the object in a stable position before release so the initial velocity is constant.  |

|   |   |
|---|---|
| (Experiment 05) The upper string might not be parallel to the ground as it is just an estimate by the human eye. Hence, the value of $h$ would be inaccurate.   | A ruler and a set square can be used to ensure that the string is perpendicular to the retort stand, which is perpendicular to the tabletop. Hence, this makes the values of $h$ more accurate. |
| (Experiment 07) <ol style="list-style-type: none"> <li>1. It is difficult to ascertain the extreme position of the ball accurately as it is only at rest instantaneously. This results in imprecision.</li> <li>2. It is difficult to release the ball with constant height.</li> </ol> | <ol style="list-style-type: none"> <li>1. Use of a motion sensor/video.</li> <li>2. Use of a release mechanism.</li> </ol>  |
| (Experiment 13) Kinks in the wire.  | Use a wingbolt to tighten the wire.   |
| (Experiment 15) The paper cone is flimsy and cannot hold a perfect circular shape at the base of the cone. Hence, this causes the values at $\theta$ to be smaller than expected. So, precision is lost for the values of $h$ , $y$ , and $x$ .   | Use a plastic cone, so that the measurements for $h$ , $x$ , and $y$ are more precise, as the shape of the cone cannot change.  |

**Table 20.5:** Additional examples of sources of errors and the corresponding solutions.

## 20.4 Planning questions

| Context   | Sentence  |
|---|---|
| A solar panel heats water by absorbing intra-red radiation from the Sun. It consists of an array of pipes, through which water is passed... Design an experiment to determine the efficiency of a model solar panel.  | Check that there is a significant temperature difference between the two thermometers. If not, adjust the power of the lamp. This will help us to determine the range of suitable values of intensity that can be used. |
| The efficiency of a motor is thought to depend on the angular velocity $\omega$ of the motor. The relation between the efficiency and the angular velocity $\omega$ of the motor may be written in the form $\eta = a\omega^b$ , where $a$ and $b$ are constants... | Check for the appropriate masses and heights such the mass can be raised when adjusting the angular speed of the motor using the variable power supply.   |

**Table 20.6:** Examples on preliminary readings.

- For *short* planning questions, we can reference the question's diagram(s). But we must include *our own* for *long* planning questions.

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