H2 Physics Summary

(Definitions, Equations, Terms, Qualitative Explanations, Common Mistakes)

Key: ( ) optional but good to include; { } Tutor's comments/Common Mistakes; [ ] Alternative Term

Topic 1: Measurement

1. **Base units**: are (a choice of well-defined) units by which all other units are expressed.
   Derived unit: a unit expressed as a product and/or quotient of the base units.

   Need to recall certain prefixes & their decimal equivalents**:**
   eg: pico / p for 10^{-12} ; giga / G for 10^{9}; tera / T for 10^{12}

   Need to make *reasonable estimates* of certain physical quantities included within syllabus. {N08P1Q2, N09P1Q2}

2. **Random error**:
   - An error {not reading} which causes measurements to be sometimes larger than the true value and sometimes smaller than the true value. Eg. parallax error.
   - Can be *reduced* by taking the average of repeated readings.
   - Often arises due to the imperfections of the observer.

   Systematic error:
   - An error {not reading} which causes measurements to be either, always larger than the true value, or always smaller than the true value.
   - *Cannot be reduced* by taking the average of repeated measurements but can be *eliminated* {for eg, by checking the instrument in which the error is suspected, against a known reliable instrument} Eg. zero error.
   - Often arises due to the imperfections of the instrument. Eg incorrect calibration of the scale.

3. **Accuracy**:
   - refers to the degree of agreement between the result of a measurement and the true value of the quantity. {If several readings of a quantity are taken, the "result of the measurement" refers to the mean value of the readings.}
   - is a measure of the magnitude of the systematic error present; high accuracy implies a small systematic error.

   Precision:
   - refers to the degree of agreement [scatter, spread] of repeated measurements of the same quantity. {NB: regardless of whether or not they are correct with respect to the true value.}
   - is a measure of the magnitude of the random errors present; high precision implies a small random error.

4. For a quantity $x = (2.0 \pm 0.1)$ mm,

   Actual [Absolute] uncertainty, $\Delta x = 0.1$ mm

   Fractional uncertainty, $\frac{\Delta x}{x} = 0.05$

   Percentage uncertainty, $\frac{\Delta x}{x} \times 100\% = 5\ \%$

If $p = (2x + y) / 3$, or $p = (2x - y) / 3$, Actual uncertainty, $\Delta p = (2\Delta x + \Delta y) / 3$

If $r = 2xy^3$ or $r = \frac{5x}{y^3}$, Fractional uncertainty, $\frac{\Delta r}{r} = \frac{\Delta x}{x} + \frac{3\Delta y}{y}$

5. **Actual uncertainty** must be recorded to <u>only 1 significant figure</u> (1 sf).

The **number of sig fig** to be recorded for a **calculated quantity** x is determined by the position of the last digit of its actual error Δx.

Eg: If g has been calculated to be 9.80645 m s^{-2} & Δg has been calculated to be 0.04848 m s^{-2}, then, Δg should be *recorded* as 0.05 m s^{-2} {1 sf } & g must then be recorded as (9.81 $\pm$ 0.05) m s^{-2}.
If Δg = 1.23 m s^{-2}, then g should be recorded as (10 $\pm$ 1) m s^{-2}.

If the actual uncertainty is recorded (to 1sf) to its *tenth or hundredth place*, the number of sf for its calculated quantity should follow to its tenth or hundredth place respectively.

Eg: If speed of sound, v has been calculated to be 330.80645 m s^{-1} &
Δv has been calculated to be 11.12 m s^{-1}, Δv must be recorded as 10 m s^{-1} {1 sf };
v must then be recorded as (330 $\pm$ 10) m s^{-1}.
If Δv = 102 m s^{-1}, then v should be recorded as (300 $\pm$ 100) m s^{-1}.

6. A **scalar quantity** is a quantity which has <u>only magnitude but no direction.</u>

A **vector quantity** has <u>both</u> magnitude and direction and thus is only completely described if both its magnitude & direction are known.

7. **Vector Subtraction**
Eg, Change in Momentum = Final momentum – Initial momentum, {not the other way round; must recall the *sequence of steps* in the 'drawing method'}

<u>Topic 2: Kinematics</u>

1. **Displacement** is defined as the <u>distance moved in a specific direction</u>.
Distance travelled is the total length covered irrespective of the direction of motion.

2. **Speed** is defined as the distance travelled per unit time OR the <u>rate of change of distance travelled</u> (with respect to time).
{N04P3Q1: Explain why it is technically incorrect to define speed as distance *per second*. 1 m}

Velocity is defined as the displacement per unit time OR the <u>rate of change of displacement</u> (with respect to time).
{NOT: displacement "over time", nor displacement "per second", nor "rate" of change of displacement "per unit time", nor speed in a particular direction, nor rate of change of "distance".}

The <u>gradient</u> of a displacement-time graph is the instantaneous <u>velocity</u>.
The <u>area</u> under a velocity-time graph is the <u>change in displacement</u>.

3. **Acceleration** is defined as the rate of change of velocity (with respect to time).

   The gradient of a velocity-time graph is the instantaneous acceleration.
   The area under an acceleration-time graph is the change in velocity.

   *Questions on *x-t* , *v-t* and *a-t* graphs are important [Reminder].

4. Equations of motion:

(1)	$v = u + a t$	derived from definition of acceleration: $a = (v - u) / t$
(2)	$s = ½ (u + v) t$	derived from the area under the *v-t* graph
(3)	$v^2 = u^2 + 2 a s$	derived from equations (1) and (2)
(4)	$s = u t + ½ a t^2$	derived from equations (1) and (2)

   Conditions to apply these equations: motion in a straight line and magnitude of the acceleration is constant. {Eg, air resistance must be negligible}

   Note: refer to the "suggested strategy for solving kinematics problems" section in the lectures.

5. **Projectile Motion** – important equations**:**

   At any instant: instantaneous velocity, $v = \sqrt{v_x^2 + v_y^2}$

   $\tan\theta = \frac{v_y}{v_x}$ (θ: direction of tangential velocity wrt horizontal) {NOT: $\tan\theta = \frac{s_y}{s_x}$}

   Must know how to apply kinematics equations to horizontal & vertical motions to determine maximum height, total time of flight, range, etc.

6. A body must be projected at an angle of **45°** to the horizontal if it were to achieve the **maximum range** on flat ground. If one of the angles is θ, then the alternative angle of projection is always (90^o- θ).

7. **Air resistance** acts against both the horizontal and vertical motions. Hence the body's maximum height is reduced and the maximum range is also reduced.

Topic 3: Dynamics

1. **Newton's First Law:**
   Every object continues in a state of rest or constant speed in a straight line unless a net (external) force acts on it.

2. **Newton's Second Law**:
   The rate of change of momentum of a body is (directly) proportional to the net force acting on the body, and the (rate of) change of momentum takes place in the direction of the force.

3. **Force** on a body is defined as the rate of change of momentum of the body {i.e. $F = \frac{d(mv)}{dt}$} and it acts in the direction of the change in momentum. {N2010 P3 Q6a, 2 m}
   Unit: newton (N). Vector quantity.

- For a finite time interval *t* and a constant mass: $F = \frac{m(v-u)}{t} = ma$
- If mass is "changing" (at $\frac{dm}{dt}$) with constant velocity *v* {as in rocket engine}: $F = v\frac{dm}{dt}$
  - o Note: this equation is often applied to calculate the *thrust, lift* of rockets, helicopters, or force on water stream, or force on luggage placed on conveyor belts.

- The (i.e. One) **newton** is defined as the force needed to accelerate a mass of 1 kg by 1 m s^{-2}.

4. Newton's Third Law:
When body X exerts a force on body Y, object Y exerts a force that is equal in magnitude and opposite in direction on object X.

- These two forces, called an action-reaction pair, always act on different objects;
- hence, they cannot cancel each other out.
- They are of the same type of force {so if the action force is a gravitational force, the reaction must also be gravitational in nature}
  {Must know how to identify forces which are an action-reaction pair; *weight and the normal reaction are not an action-reaction pair!* }

5. Linear momentum of a body is defined as the product of its mass and velocity. i.e. $p = m\,v$
Unit: kg m s^{-1}. Vector quantity.

6. Impulse of a force *I* is defined as the product of the force and the time Δt during which it acts.
i.e. $I = F \times \Delta t$ {for force which is constant over the duration Δt}

Unit: newton second (N s). Vector quantity.

- For a variable force,
  Impulse = area under the *F-t* graph { $\int F\,dt$ }
- It is equal in magnitude to the change in momentum of the body.
  {Incorrect to *define* impulse as change in momentum}
- Hence the change in momentum of the body is equal in magnitude to the area under a (net) force-time graph.
- {For *F-t* graph of irregular shape, use "count-the-squares" method to determine the area}

7. Weight is the force of gravitational attraction by the Earth on a body.
Mass: a measure of the amount of matter in a body; it is the property of a body which resists change in motion.

8. Principle of Conservation of Linear Momentum (PCLM):
When objects of a system interact, their total momentum before and after interaction are equal if no net external [resultant] force acts on the system.

or, the total momentum of an **isolated system** is constant,

i.e. $m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$, if net $F = 0$ {for all collisions}

NB: Total momentum *during* the interaction is also conserved. {See N08P1Q6}

9. Types of collisions:

(Perfectly) elastic collision	Both momentum and kinetic energy of the system are conserved.
Inelastic collision	Only momentum is conserved, total kinetic energy is not conserved.
Perfectly inelastic collision	Only momentum is conserved, and the particles stick together {move with the same velocity} after collision.

For **all *elastic*** collisions,

- $u_1 - u_2 = v_2 - v_1$ {where u_1, u_2, v_2 and v_1 are all *vectors*}

  i.e. **relative speed of approach = relative speed of separation**
- total kinetic energy of the system is conserved

  $\frac{1}{2} m_1 u_1^2 + \frac{1}{2} m_2 u_2^2 = \frac{1}{2} m_1 v_1^2 + \frac{1}{2} m_2 v_2^2$

  {more tedious than the equation above}

<u>Topic 4: Forces</u>

1. **Field of force:** a region of space within which a force is experienced.
   - **Gravitational field:** A region of space in which a *<u>mass</u>* experiences an attractive force due to the effect of another mass.
   - **Electric field:** A region of space where *an* <u>electric *charge*</u> experiences an (attractive or repulsive) force due to the effect of another charge.
   - **Magnetic field**: A region of space in which a *<u>moving electric charge</u>* or a current-carrying conductor experiences a force (that is perpendicular to the magnetic field).

2. **Types** of Forces:
   - Normal reaction: always perpendicular to the surface.
   - Reaction force: vector sum of normal reaction and friction.
   - Friction: always opposes relative motion; dissipative in nature.

     Viscous force (drag): present when an object moves through a fluid. E.g. air resistance. Magnitude of viscous force increases with the speed of the object. {Note**:** in general, the viscous force is neither $\propto v^1$, nor $\propto v^2$; these 2 relations are for certain specific cases only}.

     Origin of air resistance (Specimen Paper 07P3Q2, 1m): It arises because of the force exerted on a moving body due to the collisions of the body and the air molecules in its path.
   - Tension and compression: acts along the string, away from (for tension)/ towards (for compression) the object.

3. **Hooke's law**:

   If the limit of proportionality {Examiner may use "elastic limit"} is not exceeded, the extension (produced in a material) is directly proportional to the force/ load applied.

   i.e. $F = k\,x$ {k: force constant; spring constant, for a spring. x can also be the compression}

4. **Change in Elastic potential energy/ Strain energy** = Area under the *F-x* graph

   {Use "count the squares" method to get area}

   $= \frac{1}{2} F\,x = \frac{1}{2} k\,x^2$ {only for material that obeys Hooke's law}

5. **Pressure difference,** $p = \rho g h$ Unit: pascal (Pa). Scalar quantity.

6. **Upthrust**: An upward force exerted by a fluid on a submerged or floating object due to the difference in pressure between the upper and lower surfaces of the object.

7. **Archimedes' Principle:** Upthrust = weight of the fluid displaced by submerged {or floating} object.

   i.e. $Upthrust = V_{\text{displaced}} \times \rho_{\text{fluid}} \times g$

8. **Flotation Principle:** Upthrust = weight of object, since object is in vertical equilibrium.

9. **Terminal Velocity** (v_t) of falling object:
   At terminal velocity, Weight = Upthrust + $k\,v_t^n$ {FYI: $k\,v_t^n$ *:viscous force,* *n*: unknown constant}

10. **Moment of a force:** The product of the force and the perpendicular distance of its line of action from the pivot/ axis of rotation. Unit: newton metre (N m).

    Torque of a couple: The product of one of the forces of the couple and the perpendicular distance between the lines of action of the forces.
    - **A Couple** is a pair of equal and opposite forces, whose lines of action do not coincide. Hence it tends to produce rotation only

11. **Conditions for Equilibrium** of an "extended" object {i.e. not a point mass} (N06P2Q6a):
    (1) The resultant force acting in any direction equals zero. {translational equilibrium}
    (2) The resultant moment about any point equals zero. {rotational equilibrium}

    Principle of Moments:
    For a body to be in rotational equilibrium, the sum of all the anticlockwise moments *about any point* must be equal to the sum of all the clockwise moments about that same point. {must explicitly state the point used for pivot in problem solving!!}
    - {Exam Tip: If a force, of either unknown magnitude or direction, acts on a body, it is often necessary/ convenient to take moments about a certain pivot through which this unknown force acts to "eliminate its moment".}

12. **Centre of Gravity** of an object is defined as that single point through which the entire weight of the object may be considered to act.

13. If a mass is acted upon by 3 forces *only* and is in equilibrium, then
    - the lines of action of the 3 forces must pass through a common point (i.e. concurrent forces).
    - When a vector diagram of the three forces is drawn, the forces will form a closed triangle (vector triangle), with the vectors pointing in the same orientation around the triangle.

Topic 5: Work, Energy & Power

1. **Energy** is the ability to do work. Unit : joule (J). Scalar quantity.

2. **Principle of conservation of energy (PCE) :** Total energy of an *isolated* system remains constant; energy may be transferred from one form to another, but never created nor destroyed.
   - Need to know energy transformations /conversions in various scenarios.

3. Kinetic energy, $KE = \frac{1}{2} m v^2$

{need to derive using: definition of work; work converted to KE only, & $v^2 = u^2 + 2as$}

4. Potential Energy (PE) is defined as the stored energy available to do work.

5. To distinguish **Gravitational PE** & **Elastic PE**:

- GPE is the potential energy possessed by a mass due to its position {or height or distance} *in the field of another mass*
- EPE of a system is due to its deformation {or stretching or compression}.

6. GPE change, $GPE = mgh$ where g remains constant over distance h.

- {need to derive, using: definition of work; work converted to GPE only}
- & that the Force exerted by the external agent = mg in magnitude, since there is equilibrium}

7. The PE, U, of a body in a force field {whether gravitational or electric field} is related to the force F it experiences by: $F = -\frac{dU}{dx}$

8. Work done by a force (on a system) is defined as the product of the force and displacement in the direction of the force. i.e. $W = Fx \cos\theta$ Unit: joule (J). Scalar quantity.

- Positive work is said to be done by F if the displacement x, or its component, is parallel to F.
- Negative work is said to be done by F if x or its component is anti-parallel to F.
- No work is done if F and x are perpendicular to each other.
- By PCE, work done on a system, in general = KE gain/loss + GPE gain/loss + Thermal Energy generated (i.e. work done against friction) (if any)
- If a variable force F produces a displacement in the direction of F, the work done can be found from the **area under *F-x* graph**. $W = \int F\,dx$ = Area under F –x graph. {May need to determine the area by "counting the squares"}
- Work done on / by gas, in general, $W = \int p\,dV$. For work done by a gas expanding against a constant external pressure, $W = p\,\Delta V$

9. Power is defined as the work done per unit time {Not **"**work done per *second***"**}, or the rate at which energy is transferred with respect to time. i.e. $P = \frac{W}{t} = \frac{E}{t}$ Unit: watt (W). Scalar quantity.

10. Average Power (over a given time interval) = $< P > = \frac{\Delta W}{\Delta t} = \frac{\Delta E}{\Delta t}$

11. Instantaneous Power, $P = \frac{dW}{dt} = \frac{dE}{dt}$ or $P = Fv$ {To derive from definitions of power & work}

- for object moving at constant speed: F = applied force {eg. engine thrust}
  = total resistive force {since it is in equilibrium}
- for object beginning to accelerate: F = total resistive force + ma {N07P1Q10,N88P1Q5}

12. Efficiency: The ratio of (useful) output energy of a machine to the input energy.

i.e. = $\frac{\text{(Useful) Output Energy}}{\text{Input Energy}} \times 100\,\% = \frac{\text{(Useful) Output Power}}{\text{Input Power}} \times 100\,\%$

Topic 6: Motion in a Circle

1. **Angular displacement** θ is defined by $\boxed{\theta = \frac{s}{r}}$ Unit: radian (rad). Vector quantity.

   {Illustrate with a circle with θ, s & r labelled}
   - One (the) **radian** is defined as the angular displacement of an object in circular motion where the ratio of the arc length *s*, and the radius *r*, is equal to 1 {N08P3Q2a Old Syllabus} or, the angle (subtended) at the centre of a circle by an arc equal to the radius of the circle.
   - For one complete revolution, an object rotates through 360°, or 2π rad.

2. **Angular velocity** ω is defined as the rate of change of angular displacement (about the centre of the circle) with respect to time. i.e. $\boxed{\omega = \frac{\theta}{t}} = \frac{2\pi}{T}$ (for a complete revolution)

3. **Linear** [or tangential] **velocity**, $\boxed{v = r\,\omega}$
   is the instantaneous velocity at any point in its circular path.

   The velocity of a body moving in a circle at a constant speed changes since its direction changes. It thus experiences an acceleration**,** a net force and a change in momentum.

4. **Centripetal acceleration,** $\boxed{a = r\,\omega^2 = \frac{v^2}{r}}$ (in magnitude)

5. **Centripetal force :**
   refers to the resultant of all the forces that act on a system in circular motion.
   {It is not a particular force; "centripetal" simply means "centre-seeking". Also, when asked to draw a diagram showing all the forces that act on a system in circular motion, it is wrong to include a force that is labelled as "centripetal force". }

   - In presenting a solution involving Centripetal force $\boxed{F = m\,r\,\omega^2 = m\frac{v^2}{r}}$
     it is essential to begin with:
     "The centripetal force is provided by…. {resultant of some named forces, eg. tension, friction, gravitational force, magnetic force, etc}.
   - Solve problems involving circular motion on a banked road, aeroplane turning, conical pendulum by forming 2 equations:

     Horizontally, Centripetal force = $m\,r\,\omega^2$ *or* $m\frac{v^2}{r}$;

     Vertically, there is equilibrium of forces.

6. **Weightlessness:**
   E.g. Explain why a person in a satellite orbiting the Earth experiences "weightlessness" although the gravitation field strength {*g*} at that height is not zero:
   - because the person and the satellite would both have the same acceleration; hence the normal reaction on the person is zero.
     {To elaborate: the sensation of weight is due to the normal reaction exerted on the object. When the person & the floor of the satellite have the same acceleration, the contact force between them is zero, hence the normal reaction is zero. This is the state of "weightlessness".}

Topic 7: Gravitational Field

1. Newton's law of gravitation:

The (mutual) gravitational force of attraction *F* between two point masses *M* and *m* separated by a distance *r* is given by

$$F = \frac{GMm}{r^2}$$

where *G* is the Universal gravitational constant (given in data list), 6.67 x 10^{-11} N m^2 kg^{-2}

or, the (mutual) gravitational force of attraction between two point masses is proportional to the product of their masses & inversely proportional to the square of their separation.
{Must include "point masses" - N09P3Q5aii}

- Note that *r* refers to the distance between the *centres* of the masses.

2. Gravitational field strength, *g*

at a point is defined as the gravitational force per unit mass at that point. {NOT: "force *on* unit mass"}

$$g = \frac{F}{m}$$

Unit: N kg^{-1}. Vector quantity.

Field Strength due to a point mass *M*, $g = \frac{GM}{r^2}$

- Need to derive from Newton's law of gravitation & definition of *g* (N09P3Q5a);
- Up to about 1000 m from the Earth's surface, *g* (= 9.81 N kg^{-1}) can be taken to be constant.

Explain why "effective g" or apparent weight at equator < at poles:
{Need to understand the effect of Earth's rotation on the "apparent weight", & apparent weight is the normal reaction on an object by the Earth's surface: refer to N07P3Q5c (i), p 63 in "Worked solution" of 2010 edition.}

3. Gravitational potential, ϕ

at a point is defined as the work done (by an external force) in bringing unit mass from infinity to that point (without changing its KE). {Not: a unit mass!} Muncaster supports this!}

$$\phi = \frac{W}{m}$$

{Exam Report for 2012 P3Q7a(ii) seems to frown on such an ans }

Explain why gravitational potential values are *always negative*?

- Potential of any point at infinity is defined {that means, arbitrarily assigned} to be zero. {N2011P3Q6a}
- As the gravitational force is attractive, the work done by an external agent in bringing unit mass from infinity to any point in the field will be negative (as the restraining force exerted by the external agent is opposite in direction to the displacement)
- Since the work done is negative and potential is the work done per unit mass, gravitational potential values are always negative.

Gravitational potential due to a point mass *M*, $\phi = -\frac{GM}{r}$ {The negative sign must not be omitted}

Relation between *g* and ϕ: $g = -\frac{d\phi}{dr}$ = - gradient of ϕ-*r* graph

4. **Gravitational potential energy *U*** of any mass *m* at a point in the gravitational field of another mass *M*, is the work done in bringing *that* mass *m* {NOT: "*unit mass*", or "*a mass*"} from infinity to that point.

$$U = m\,\phi = -\frac{GMm}{r}$$

Relation between *F* and *U*: $F = -\frac{dU}{dr}$ = - gradient of *U*-*r* graph

5. **Change in GPE,** $\Delta U = m\,g\,h$
{only where *g is constant* over the distance *h*; otherwise, must use: $\Delta U = m\phi_f - m\phi_i$ }

6. **Total Energy** of a Satellite = **GPE + KE**

$$= \left(-\frac{GMm}{r}\right) + \left(\frac{1}{2}\frac{GMm}{r}\right) = -\frac{1}{2}\frac{GMm}{r}$$ {N08P2}

{Need to know how to show: KE = $\frac{1}{2}\frac{GMm}{r}$ = - ½ GPE}

7. **Escape speed** $v = \sqrt{2gR} = \sqrt{\frac{2GM}{R}}$ (Since $g = \frac{GM}{r^2}$)
{Need to show by PCE & definition of escape speed; recall & use is not allowed - Specimen Paper 2 Q2c}

8. For a satellite in circular orbit, "the centripetal force is provided by the gravitational force"

Hence $\frac{GMm}{r^2} = \frac{mv^2}{r}$

$$= m\,r\,\omega^2 = m\,r\left(\frac{2\pi}{T}\right)^2$$

$\Rightarrow T^2 \propto r^3$ { known as Kepler's 3rd law- not required to know this name}

Explain why a satellite does not move in the direction of the gravitational force:
i.e. why does it stay in its circular orbit, and not fall towards the Earth?
Ans: because the gravitational force exerted by the Earth on the satellite is *JUST sufficient to cause the centripetal acceleration.*

{Misconception: to think that motion (i.e. velocity) must always be in the direction of the net force. Newton's 2nd law only requires the (rate of) change in momentum, & hence the CHANGE in velocity, to be in the direction of the net force. {The direction of the vector, *change in velocity*, is not the same as that of the initial velocity, in general.}
Illustration: direction of motion in a parabolic motion is not in the direction of the net force}

Why Satellites, as they gradually lose energy due to small resistive forces, may eventually 'burn up' in the Earth's atmosphere? [4m] {2011P3Q6d}

9. **Geostationary satellite** is one which is always above a certain point on the Earth as the Earth rotates about its axis.
For a geostationary orbit, satellite must
- lie in equatorial plane of Earth
- rotate from west to east
- with a particular period {24 hours for Earth} {Note these 3 conditions}

A *particular* value of the period implies that the orbital radius (& height), angular speed *w* & centripetal acceleration are fixed values. However, the mass of the satellite does not have to be any particular value & hence its KE, GPE, & the centripetal force are also not fixed values, since their values depend on the mass of the geostationary satellite.

Explain why a geostationary orbit must lie in the **equatorial plane** of the earth:

- The force of attraction to the Earth is to its centre so the circular orbit must be centred on the Earth's centre.
- The plane of the orbit must lie in the equatorial plane of the Earth; otherwise it would have a varying latitude (and thus not be geostationary). {N2003 P3Q2 c}

Topic 8: Thermal Physics

1. If two bodies are in **thermal equilibrium**, there is no *net* flow of thermal energy between them and they have the same temperature. {NB: this does not imply they must have the same *internal energy* as internal energy depends also on the number of molecules in the 2 bodies, which is unknown here}

2. Thermodynamic (Kelvin) scale / absolute scale of temperature is the theoretical scale that is independent of the properties of any particular substance.

- To convert Kelvin to degrees Celsius: $T/K = T/^{0}C + 273.15$
- **Absolute zero:** Temperature at which all substances have a minimum internal energy {NOT: zero internal energy}

3. Specific heat capacity (c) is defined as the amount of energy needed to produce unit temperature change for unit mass {NOT: 1 kg} of a substance, without causing a change in state,

i.e. $c = \dfrac{Q}{m\Delta T}$

4. Specific latent heat of vaporisation (L_v) is defined as the energy per *unit* mass required to change a substance from liquid phase to gaseous phase without a change of temperature.

5. Specific latent heat of fusion (L_f) is defined as the energy per *unit* mass required to change a substance from solid phase to liquid phase without a change of temperature.

i.e. $L = \dfrac{Q}{m}$ {for both cases of vaporisation & melting}

6. The **mole** is the amount of substance that contains the same number of particles as the number of atoms in 0.012 kg (or 12g) of carbon-12.

- Avogadro constant (N_A) = 6.02×10^{23} mol^{-1}
- No. of moles, n = $\dfrac{\text{Mass of Substance}}{\text{Molar Mass}}$ = $\dfrac{\text{No. of atoms or molecules}}{\text{Avogadro Constant}}$

7. Ideal Gas Equation: $pV = nRT$ or $pV = NkT$

where p: pressure (Pa)
V: volume (m^3)
n: amount of gas (mol), NOT: number of moles
R: molar gas constant (8.31 J K^{-1} mol^{-1}, in List of Data)
T: *absolute* temperature (K)

An **ideal gas** is one that obeys the equation $pV = nRT$ for all values of pressure, volume and temperature

8. 'State' refers to the thermodynamic properties of pressure, volume, temperature and number of molecules.

9. **Average KE of one molecule** of an ideal gas = ½ m <c^2> = $\frac{3}{2} k T$ {with T in K, not °C, in List of Formulae} (mass of molecule = m ; mean square speed = <c^2>)

10. **Internal Energy (U) of a substance:**
is the sum of the kinetic energy of the molecules due to their random motion and the potential energy of the molecules due to the intermolecular forces.

- "Internal energy is determined by the **state of the system**". Explain what this means.
  Ans: Internal energy is determined by the values of N & T of the current state, ie it is independent of the path taken to reach its current state. Thus if a system undergoes a change from one state to another {for eg, from point A on p-V graph to another point B}, its change in internal energy is the same, regardless of which path it has taken to get from A to B.

- For an ideal gas, internal energy U = Sum of the KE of all the molecules only {since PE = 0, due to zero intermolecular forces}

  i.e.. $U = E_k = \frac{1}{2} N m <c^2> = \frac{3}{2} N k T = \frac{3}{2} n R T$ (for a monatomic ideal gas)

  $\Rightarrow$ $U \propto T$ (for a fixed number of molecules) (mass of a molecule, m)

  $\Rightarrow$ $\frac{U_1}{U_2} = \frac{T_1}{T_2}$

  Similarly, $\Delta U \propto \Delta T$

  U depends on T and number of molecules N.

N2001 P1Q26: Which statement about internal energy is correct?
A The internal energy of a system can be increased without transfer of energy by heating.
B The internal energy of a system depends only on its temperature.
C When the internal energy of a system is increased, its temperature always rises.
D When 2 systems have the same internal energy, they must be at the same temperature.
Ans: A {Need to understand why the other options are incorrect.}

11. **First Law of Thermodynamics**:
The increase in internal energy of a system is equal to the sum of the heat supplied to the system and the work done on the system.

i.e. $\Delta U = W + Q$

Quantity	**Is Positive**	**Is Negative**	**Is Zero**
ΔU : increase in internal energy of the system	Increase in internal energy (or temperature).	Decrease in internal energy (or temperature).	No change in internal energy (or temperature) of the gas, i.e. an **isothermal** process. ($\Delta U = 0$, $\Delta T = 0$)
Q: heat transferred into the system	Heat is transferred into the system.	Heat is removed from the system.	No heat transfer, i.e. an **adiabatic** process. In practice, this could occur when the system is well-insulated or the process is completed in a very short period of

			time. $\Rightarrow \Delta U = W$ (since $Q = 0$)
W: work done on the system.	Volume decreases (compression); i.e. work is done on the system.	Volume increases (expansion); i.e. work is done by the system (on the surroundings).	No change in volume (i.e. an **isochoric / isovolumetric** process). $\Rightarrow \Delta U = Q$ (since $W = 0$)

- $W = \int p\, dV$ = area under pressure-volume graph.
- If pressure is constant,

Work done by gas = $p\,\Delta V$; Work done on gas = $-p\,\Delta V$ where ΔV = change in volume.

12. ΔU for a cycle = 0 {since $U \propto T$, & $\Delta T = 0$ for a cycle }

13. Specific latent heat of vaporisation > specific latent heat of fusion for a given substance because: {N06P3Q2}

- During vaporisation, there is a greater increase in volume than in fusion;
- thus more work is done against atmospheric pressure during vaporisation.
- The greater increase in volume also means the increase in the (molecular) potential energy, & hence, internal energy, during vaporisation > that during melting.
- Hence by 1st Law of Thermodynamics, heat supplied during vaporisation > that during melting; hence $l_v > l_f$ {since $Q = ml = \Delta U - W$; Note that W is negative}

{Note: 1. the use of **comparative terms**: *greater*, *more*, and >
2. the increase in internal energy is due to an increase in the PE, NOT KE of molecules
3. the system here is NOT to be considered as an ideal gas system }

{Similarly, you need to explain why, when a liquid is boiling, thermal energy is being supplied, and yet, the temperature of the liquid does not change. (N97P3Q5, [4 m] }

14.

	Melting	**Boiling**	**Evaporation**
Occurrence	Throughout the substance, at a fixed temperature and pressure		On the surface, at all temperatures
Temperature & hence **KE** of molecules	Constant		Decreases for remaining molecules
PE of molecules	Increases slightly	Increases significantly	
Spacing (volume)	***Increases slightly**	Increases significantly	

Topic 9: Oscillations

1. **Period *T*,** is defined as the time taken for one complete oscillation.
2. **Frequency *f*,** is defined as the number of oscillations per unit time, $f = \frac{1}{T}$ [Hz or s^{-1}]
3. **Angular frequency ω,** is defined by $\omega = 2\pi f$ where *f* is defined as the number of oscillations per unit time.
   {It is thus the rate of change of angular displacement measured in radians per sec}
4. **Amplitude**: The maximum displacement from the equilibrium position.
5. **Phase difference** [angle] $\phi = \frac{x}{\lambda} \times 2\pi = \frac{t}{T} \times 2\pi$ [rad]
   {*x* = separation between 2 wave particles in the direction of wave motion;
   t = time difference between two waves or two particles in a wave}
6. **Simple harmonic motion**:
   An oscillatory motion in which the acceleration [or restoring force] is
   - always proportional to, and
   - opposite in direction to the displacement from a certain fixed point / equilibrium position {MUST define where displacement is from}
   - i.e. $a = -\omega^2 x$ (Defining equation of S.H.M)

"Time Equations"	"Displacement Equations"
$x = x_o \sin(\omega t)$ (or $x = x_o \cos(\omega t)$) {depending on the initial condition}	
$v = \frac{dx}{dt} = x_o\omega \cos(\omega t) = v_o \cos(\omega t)$ {depending on the initial condition}	$v = \pm\omega\sqrt{x_o^2 - x^2}$ {in List of Formulae} (v - x graph is an ellipse)
$a = -\omega^2 x = -x_o\omega^2 \sin(\omega t) = a_o \sin(\omega t)$ {depending on the initial condition}	$a = -\omega^2 x$
KE = $\frac{1}{2}mv^2 = \frac{1}{2}m[x_o\omega \cos(\omega t)]^2$ {depending on the initial condition}	KE = $\frac{1}{2}mv^2 = \frac{1}{2}m\omega^2(x_o^2 - x^2)$ (KE - *x* graph is an inverted parabola)
PE = $\frac{1}{2}m\omega^2 x^2 = \frac{1}{2}m\omega^2[x_o \sin(\omega t)]^2$ {depending on the initial condition}	PE = $\frac{1}{2}m\omega^2 x^2$ {PE - *x* graph is a parabola}

Max Velocity $v_o = x_o\omega$; **Max acceleration** $a_o = x_o\omega^2$

In general, **Total Energy**, E_{total} = KE + PE at any instant = $\frac{1}{2} m\omega^2 x_o^2$ = max KE = max PE

For vertical spring-mass system,
total energy is not equal to KE_{max} although it is still equal to PE_{max}.
$E_T = E_K$ + (GPE + EPE).
{refer to lecture notes pg 19 for graphs}

7. For a **horizontal or vertical spring-mass system,**

a. **Period** is given by: $T = 2\pi\sqrt{\frac{m}{k}}$

b. Relationship between ω and k is given by: $\omega^2 = \frac{k}{m}$ (derivation not required)

where *m* = mass attached to spring;
k = spring constant

8. For a **simple pendulum**, period is given by: $T = 2\pi\sqrt{\frac{l}{g}}$

where *l* = length of the pendulum;
g = acceleration of free fall

9. Damping refers to the loss of energy from an oscillating system to the environment, caused by a dissipative force acting in opposite direction of motion of the system, eg friction, viscous force.

Light Damping: The system oscillates about the equilibrium position with decreasing amplitude over a period of time.

Critical Damping: The system does not oscillate & damping is *just* adequate such that the system returns to its equilibrium position in the shortest possible time. {Need to describe practical examples, eg, in analogue ammeters}

Heavy Damping: The damping is so great that the displaced object never oscillates but returns to its equilibrium position very very slowly.

{Need to illustrate these 3 degrees of damping with a displacement-time graph}

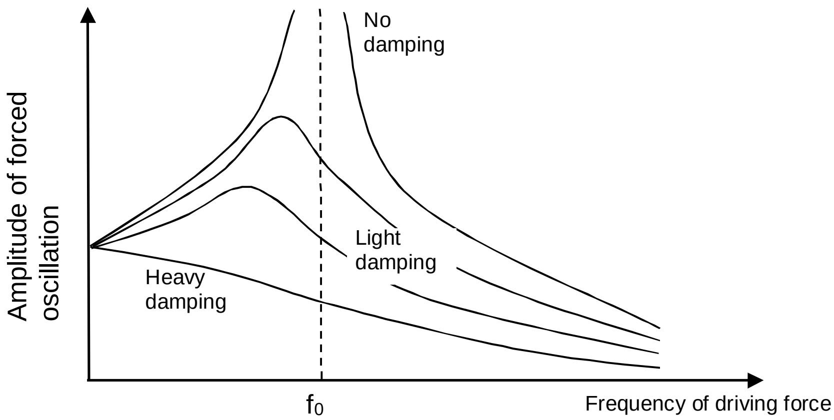
10.Free Oscillation: An oscillating system is said to be undergoing free oscillations if:
- its oscillatory motion is not subjected to an external periodic driving force.
- Hence the system oscillates at its natural frequency.

Forced Oscillation: An oscillating system is said to undergo forced oscillations if:
- it is subjected to an input of energy from an external periodic driving force.
- As a result, the frequency of the forced or driven oscillations will be at the frequency of the *driving force* [called the driving frequency] i.e. no longer at its own natural frequency.

11.Resonance:
- a phenomenon whereby the amplitude of a system undergoing forced oscillations is at a maximum.
- It occurs when the frequency of the periodic driving force is equal to the natural frequency of the system.

Effects of damping on the frequency response of a system undergoing forced oscillations:

1) resonant frequency decreases
2) sharpness of resonance [resonant peak] decreases
3) amplitude of forced oscillations decreases



A graph showing the amplitude of the driven oscillations as a function of equal driving forces (or amplitudes) at various driving frequencies.

Topic 10: Wave Motion

1. **Progressive wave**:
   is the movement of a disturbance from a source which transfers energy from the source to places around it by means of vibrations/oscillations. {Mark Scheme for N07P2Q3a, 2 m}

2. **Wavelength**: distance between 2 consecutive points on a wave which are in phase.

3. **Speed** of a wave, $v = f\lambda$ {derived from $v = \lambda / T$ and $f = 1 / T$}

   {It refers to the speed of propagation of the energy {which is constant}, in contrast to the speed of *oscillation of a wave particle* which is simple harmonic in nature, given by $v = \pm\,\omega\sqrt{x_o^2 - x^2}$ }

4. **Phase** is an angle in radians (rad) or degrees (°) which gives a measure of the fraction of a cycle that has been completed by an oscillating particle or by a wave {One cycle corresponds to 2π rad.}

5. **Phase difference** (ϕ) is a measure of how much one wave is out of step with another wave or how much one particle in a wave is out of step with another particle in the same wave. It is expressed in terms of angles from 0 to 2π radians.
   - Two particles are in phase, if they are in step with one another, i.e. zero phase difference.
   - Two particles are in anti-phase, if they are out of phase by half a cycle, i.e. π radians or 180°.

6. **Transverse wave**: a wave in which the oscillations of the wave particles {NOT: movement/motion} are *perpendicular* to the direction of the propagation of the wave.
   Longitudinal wave: a wave in which the oscillations of the wave particles are *parallel* to the direction of the propagation of the wave.

7. **Intensity** (of a wave): defined as the rate of energy flow [i.e. power] per unit cross-sectional area perpendicular to the direction of wave propagation.

   I.e. $\text{Intensity} = \dfrac{\text{Energy}}{\text{Time} \times \text{Area}} = \dfrac{\text{Power}}{\text{Area}}$ S.I. unit of intensity is W m^{-2}

   For a point source (which would emit spherical wavefronts),

   Intensity = $\dfrac{\frac{1}{2}m\,\omega^2 A^2}{t \times 4\pi r^2}$ where A = amplitude & r = distance from the point source.

   Area perpendicular to wave = surface area of a sphere = $4\pi r^2$

   For constant power,
   $I \propto \dfrac{1}{r^2}$
   Since $I \propto A^2 \rightarrow A \propto \frac{1}{r}$

   For all types of wave sources, Intensity $\propto$ (Amplitude)^2

8. **Polarisation** is said to occur when oscillations of the wave particles are only in one plane normal to the direction of propagation. {only transverse waves can be polarized}

9. **Malus' Law**: $I = I_0 \cos^2 \theta$
   When completely plane polarized light is incident on the analyzer, the intensity I of the light transmitted by the analyzer is directly proportional to the square of the cosine of angle between the transmission axes of the analyzer and the polarizer.

Topic 11: Superposition

1. **Principle of Superposition:**
   When two or more waves of the same type meet/superpose {NOT: superimpose} at a point, the resultant displacement {NOT: amplitude} of the waves is equal to the vector sum of their individual displacements at that point.

2. **Diffraction** refers to the spreading [bending] of waves when they pass through an opening [gap], or round an obstacle into the "shadow" region.
   - For significant diffraction to occur, the size of the gap $\cong$ λ of the wave.

3. **Coherent waves:** waves having a constant phase difference {not: "zero phase difference/in phase"}.

4. **Interference** refers to the superposition of coherent waves which results in a change in the overall intensity.

   For an **observable/well-defined interference pattern**, waves must be:
   - coherent
   - same amplitude {or approximately equal}
   - be unpolarised or polarised in the same direction {if waves are transverse, ie not longitudinal}
   - same type {last 2 bullets are least important}

   a) Condition for **Constructive** Interference {i.e. max intensity} at a point P:
   - phase difference of the 2 waves at P = ***(n)* 2π radians** [0, 2π, or 4π, rad etc]
   - with 2 *in-phase* sources → implies path difference = ***n*** λ**,** where n is an integer { **an integral multiple of the wavelength λ** of the waves }
   - with 2 *antiphase* sources → implies path difference = **(*n* + ½)** λ { **odd multiples of half wavelengths** }

   b) Condition for **Destructive** Interference {i.e. min intensity} at a point P:
   - phase difference of the 2 waves at P = **(*n* + ½) 2π radians** [π, 3π, 5π rad etc]
   - with 2 *in-phase* sources → implies path difference = **(*n* + ½)** λ**,** where n is an integer
   - with 2 *antiphase* sources → implies path difference = ***n*** λ

5. **Fringe separation,** $x = \frac{\lambda D}{a}$ **applicable only** if $a \ll D$ & $\lambda \ll a$

   {hence, generally applies only to Young's Double Slit interference of light, i.e. NOT for microwaves, sound waves, water waves. **However, see 2009 P1Q24 on radiowaves**. }

   - Note: phase difference between the 2 waves (from the double slit) at any point X (on the screen), lying between the central maximum & the 1st maximum, is (approximately) proportional to the distance between X and the central maximum {N2001P2Q5b(ii) & N2006 P2Q6b}.
   - Using 2 waves of equal amplitude x_o, the resultant amplitude of the central *bright* fringe is doubled {$2x_o$}.
     Also the resultant intensity increases by *4 times* {not 2 times} since $I_{resultant} \propto (2\,x_0)^2$ }

6. **Stationary (standing) wave** is one
   - whose waveform/wave profile does not advance /move,
   - where there is no net transport of energy, and

- where the positions of antinodes and nodes do not change, or where there are certain points which are permanently at rest. {last bullet is least impt}

A stationary wave is formed when two progressive waves of the same frequency**,** amplitude and speed, travelling in opposite directions are superposed.

{Assume "boundary conditions" are met, for eg, $n\frac{\lambda}{2}$ = distance between source & reflector, for stationary waves in a stretched string}

Differences between stationary waves & progressive waves:

	Stationary Waves	Progressive Waves
Amplitude	Varies from maximum at the anti-nodes to zero at the nodes.	Same for all particles in the wave (provided no energy is lost).
Wavelength	Twice the distance between a pair of adjacent nodes or anti-nodes.	The distance between two consecutive points on a wave, that are in phase.
Phase [Phase angle]	Particles in the same segment/ between 2 adjacent nodes are in phase. Particles in adjacent segments are in anti-phase.	All particles within one wavelength have different phases.
Wave Profile	The wave profile does not advance.	The wave profile advances.
Energy	No energy is transported by the wave.	Energy is transported in the direction of the wave.

- **Node**: a region of destructive superposition where the waves always meet out of phase by π radians**.** Hence displacement here is permanently zero {or minimum}

- **Antinode:** a region of constructive superposition where the waves always meet in phase**.** Hence a particle here vibrates with maximum *amplitude*.
  {but it is NOT a point with a permanent large displacement! J08P2Q5b, 1m}

- **Distance between 2 successive nodes/antinodes = λ/2**

- Need to know relation between λ, length of pipe L, & end correction in both open & closed pipes
  {N09P1Q22} Eg, for fundamental mode in closed pipe: $\frac{\lambda}{4}$ = L + c if end correction c is not negligible

- For stationary sound waves: **maximum pressure change** occurs at the **nodes** {NOT at the antinodes} because every node changes from a point of compression to become a point of rarefaction half a period later {N05P3Q3c; N08P1Q22; Prelim 2011 P1Q16: must know how to deduce from a displacement-position graph, the positions of the nodes and antinodes }
  At antinodes, there is **no variation** in pressure.

7. For a **diffraction grating**, $d \sin\theta = n\lambda$

where d = distance between successive slits [grating spacing]
= reciprocal to *number of lines per metre*

Total no of orders [images] that can be observed = $2n_{max} + 1$, where n_{max} : max order of diffraction

- When a *white* light passes through a diffraction grating, for each order of diffraction, a longer wavelength {red} diffracts more than a shorter wavelength {violet)} {as $\sin\theta \propto \lambda$}.
- Need to describe use of a grating to determine wavelength of light.

Topic 12: Current of Electricity

1. **Electric current (I)** is the rate of flow of *charge* with respect to time. {NOT: charged particles!}
   Scalar; S.I unit : ampere (A).

2. **Electric charge (Q)** is defined as the product of the (steady) current at that point and the time for which the current flows,
   i.e. $Q = I\,t$ Scalar; S.I unit : Coulomb (C)

   where $Q = N\,e$ (i.e. number of charged particles x charge per particle)

3. **One Coulomb (C)** is defined as the amount of charge flowing per *second* pass a point in a circuit at which the current is one ampere.
   i.e. 1 C = 1 A x 1 s.

4. $I = n\,A\,v\,e$
   (where n = number density, A = cross-sectional area, v = drift velocity, e = electronic charge)

5. **Potential difference** is defined as the energy per unit charge transferred from electrical energy to other forms of energy when charge passes through an electrical component,

   i.e. $V = W\,/\,Q$ Scalar; S.I unit : volt (V)

   or, is the electric power per unit current transferred to other forms of power when the current passes through an electrical component,
   i.e. $V = P/\,I$

   {Need to *distinguish* between potential difference & e.m.f. in terms of energy considerations}

   One **Volt** is defined as the potential difference 2 points in a circuit in which one joule of energy is converted when one coulomb passes from one point to the other,
   i.e. 1 volt = one joule per coulomb {for MCQ}

6. **Electromotive force** (e.m.f.) is defined as the energy transferred per unit charge from other forms of energy into electrical energy by a source when charge is moved round a complete circuit.

   i.e. $E = W\,/\,Q$ Scalar; S.I unit : volt (V)

   For a cell with internal resistance,
   e.m.f. = terminal p.d. + p.d. across internal resistance

7. **Resistance** is defined as the *ratio* of the potential difference across a component to the current flowing through it ,
   i.e. $R = V\,/\,I$ Scalar; S.I unit : ohm (Ω)

   - It is NOT the gradient of a *V-I* graph in general; hence, NOT = $\dfrac{1}{\text{gradient of } I - V \text{ graph}}$
   - however, if the *V-I* graph of a conductor is linear AND passes through the origin, then the ratio $\dfrac{V}{I}$ = the gradient for this special class of conductors {called ohmic conductors}.
   - Hence the resistance at any point on an *I-V* graph = the reciprocal of the gradient of the line that joins that point to the origin.

One **Ohm** is the resistance of a conductor when a potential difference of one volt drives a current of one ampere through it.
i.e. 1 Ω = one volt per ampere {for MCQ}

8. Ohm's law: The current in a component is directly proportional to the potential difference across it provided physical conditions (eg temperature) stay constant. (June 07P1Q31)

9. Effect of temperature on resistance:

a. For metallic conductors: resistance increases with increasing temperature, mainly due to higher rate of collision of charge carriers with lattice ions, and this effect outweighs the increase in the number of mobile charge carriers. {2012 P3 Q5(a) 4m}

b. For semiconductors: resistance decreases with increasing temperature, due to increased abundance of electrons and holes. {2012 P3 Q5(b) 3m}

10. I-V Characteristics of 4 cases: need to sketch & explain their shape.

1) For metallic conductor maintained at constant temperature: Resistance is constant.
2) Filament lamp: Resistance *increases* as temperature increases.
3) Semiconductor: Resistance *decreases* as temperature increases.
4) Diode: In forward bias, a diode has low resistance. {If ideal, R = 0}
   In reverse bias, the diode has very high resistance {until the breakdown voltage is reached

11. $R = \frac{\rho l}{A}$ (for a conductor of length *L*, uniform cross-sectional area *A* and resistivity ρ)

Resistivity is defined as the resistance of a material of unit cross-sectional area and unit length.
{From $R = \frac{\rho l}{A}$, $\rho = \frac{RA}{l}$} Unlike resistance which depends on the property of the sample, (ie its length, cross-sectional area & resistivity) , resistivity depends only on the material of the sample.

12. Electrical Power,

$$P = IV = I^2 R = V^2 / R$$

Brightness of bulb is determined by the power dissipated, and not by *I, V* or *R* alone.

13. Graph of Power dissipated vs Load resistance [Max Power Transfer]

- Recall Shape of the graph –refer 2011P3Q8 for shape or Tutorial Q9 {Not stated in Syllabus but tested in 2012 P1Q28}
- Max power is transferred by an emf source to a variable resistor [load] when its resistance is set to the value of the internal resistance of the source

Topic 13: DC Circuits

1. **2 Conservation Principles** for Circuits

1) {Kirchoff's 1st law} Because *charge is always conserved*, the sum of currents entering any junction in an electric circuit is always equal to the sum of currents leaving that junction,
i.e. $\Sigma(I_{in}) = \Sigma(I_{out})$

2) {Kirchoff's 2nd law} Because *energy is always conserved*, in any closed loop in an electric circuit, sum of e.m.f.s in a loop equals the potential drops across any components.
i.e. $\Sigma(\text{e.m.f.}) = \Sigma(I\,R)$
{Need to know sign convention for e.m.f., & I R when substituting in the numerical values}

2. **Resistors in Series:** $R = R_1 + R_2 + \ldots\ldots$

Resistors in Parallel: $1/R = 1/R_1 + 1/R_2 + \ldots$

{The equivalent resistance of a parallel network is smaller than even the smallest resistor in the network}

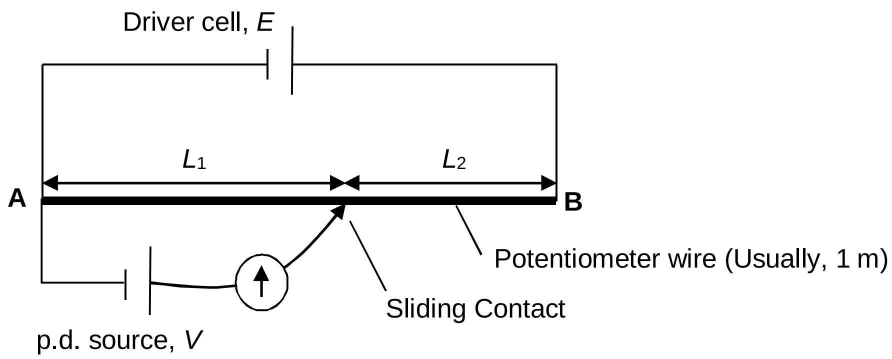
3. For **potential divider** with 2 resistors in series,

Potential drop across R_1, $V_1 = \dfrac{R_1}{R_1 + R_2} \times \text{PD across } R_1 \ \& \ R_2$

Potential drop across R_2, $V_2 = \dfrac{R_2}{R_1 + R_2} \times \text{PD across } R_1 \ \& \ R_2$

Need to explain how **LDR & thermistors** in potential dividers can be used to provide a p.d. which is dependent on illumination & temperature respectively.

4. **Potentiometer**:



If the driver cell has negligible internal resistance, and if Galvanometer shows a zero reading,

EMF or p.d. of the unknown source, $V = \dfrac{L_1}{L_1 + L_2} \times E$

p.d. being balanced = p.d. per unit length of potentiometer wire x balance length.

Topic 14: Electric Field

1. A **field of force** is a region of space in which a particle which is placed experiences a force due to the interaction between the particle's and the field's property. {N12/P3/Q7}

2. An **Electric field** is a region of space where any charged particle in it experiences an electric force.

3. Electric field lines:

1) Indicates the direction of the force a small positive test charge would experience if it is placed at that point in the electric field. {N10/ P1/Q24}.
2) Arrows on a field line should point from a positive to a negative charge.
3) Spacing between the lines indicates the strength of the field. Equally-spaced (parallel) lines indicate a uniform electric field.
4) Lines never cross one another

2. Coulomb's law: The (mutual) electric force F acting between 2 point charges, Q_1 and Q_2, separated by a distance r is given by:

$$F = \frac{1}{4\pi\varepsilon_0}\frac{Q_1 Q_2}{r^2}$$

where ε_0: permittivity of free space (8.85×10^{-12} C^2 N^{-1} m^{-2})

or, the (mutual) electric force between two point charges is proportional to the product of their charges & inversely proportional to the square of their separation.

4. Electric field strength / electric field intensity (E) at a point is defined as the electric force per unit positive charge acting on a small test charge placed at that point.

i.e. $E = F / q$ vector; S.I. unit: newton per coulomb (N C^{-1}) or volt per metre (V m^{-1})

$\rightarrow F = qE$

- Note: By "small test charge", it means the magnitude of the charge (in coulombs) must be small, so that its presence in the electric field does not distort the field. (N08/ P1/ Q24)

5. Electric field strength / electric field intensity (E) due to a point charge *Q*:

$$E = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r^2}$$

{NB: Do NOT substitute a negative charge with its negative sign in calculations!}

- Must know how to calculate the resultant E {by vector addition} at a point due to several point charges.

6. Electric potential (V) at a point is defined as the work done in moving unit positive charge from infinity to that point (without causing a change in KE).

i.e. $V = W/Q$ scalar; S.I. unit: volt (V)

- V is positive or negative depending on the polarity of the fixed charge producing the E-field. (In contrast, gravitational potential is always negative.)
- V at infinity is defined as zero.

Electric Potential due to a *point* charge *Q* : $V = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r}$ {in List of Formulae}

{NB: Must substitute *Q* with its sign!}

- The total electric potential at a point due to several point charges (Q_1, Q_2, Q_3 etc) is the algebraic/ scalar sum of electric potentials at that point, due to the individual charges.

7. **Electric potential energy (*U*)** of a charge (at a point) in an electric field is defined as the work done in moving the charge from infinity to that point.

i.e. $U = qV$

Electric potential energy possessed by a charge Q_2 placed at a point in the electric field set up by a point charge Q_1,

i.e. $U = \frac{1}{4\pi\varepsilon_0}\frac{Q_1 Q_2}{r}$

8. $\Delta U = q\,\Delta V$

Where ΔU = change in electric potential energy of a charge, *q* moved between 2 points in an electric field region, also the **Work done, *W*** on charge
ΔV = potential difference between 2 points

- A **positive** charge **placed & released** in an E field will accelerate in the direction of E & **gain KE**, while simultaneously, **lose EPE**.
- A **negative** charge caused to move {i.e. **projected**} in the direction of E will **decelerate**, i.e. lose KE & gain EPE.

9. Relation between *E* and *V*: $E = -\frac{dV}{dx}$

Where *x* = separation between the 2 points in a field (analogous to $g = -\frac{d\phi}{dx}$)

Negative sign is essential when stating the relation. The negative sign indicates that the electric field strength vector acts in the direction of decreasing potential. {**NOT:** that the electric field strength decreases in the direction of decreasing potential}

i.e. The electric field strength at a point is numerically equal to the **potential gradient** $\frac{dV}{dx}$ at that pt.

- For a pair of parallel plates, the potential decreases at a constant rate with distance from one of the plates (N07/P3/Q2).
- For a charged metal sphere, potential *V* within the sphere is constant & electric field strength is zero {due to its mobile charge carriers} { N12/P3/Q7}
- $V = -\int E\,dx$ = Area under E-x graph {N07/P2/Q2}

10. **Equipotential** surface: a surface where the electric potential is constant.

- Hence no work is done when a charge is moved along this surface. $W = q\,\Delta V$, $\Delta V = 0$

- Electric field lines must meet this surface at <u>right angles</u> {because if the field lines are not at 90^0 to it, it would imply that there is a non-zero component of E along the surface. This would contradict the fact that E along equipotential surface must = 0 }

11. Uniform electric field strength between 2 charged parallel plates.

i.e. $E = V / d$

where d = perpendicular distance between the plates,
V = p.d. between plates

Acceleration of charge where its weight is negligible, $a = \frac{qV}{md}$

12. Path of charge moving at 90^0 to electric field: parabolic.
From point where it exits the field, the path is a <u>straight</u> line, at a <u>tangent</u> to the parabola at exit.

<u>Topic 15: Electromagnetism</u>

1. **Magnetic Field**: a region (of space) where a magnetic force is experienced by a current-carrying conductor {or moving charged particle or a permanent magnet}.

   - The <u>direction</u> of a magnetic field line (i.e. the arrow) defines the direction of the <u>magnetic force on a north pole.</u> (N2010 P3Q3b)
   - Must know the magnetic flux patterns around a straight wire, circular coil, and solenoid.

2. **Magnetic flux density / Magnetic field strength, *B*** is defined as the force acting <u>per unit current</u> in a wire of <u>unit length</u> placed at <u>right-angles</u> to the field.

   i.e. $B = \frac{F}{IL}$

   {NB: If you're not able to give the "statement form", write down the above defining equation & define each symbol.}

3. Force on a current-carrying conductor, $F = B\,I\,L \sin\theta$ (θ: angle between the B and I)

   Fleming's left hand rule: Direction of the magnetic force is always perpendicular to the <u>plane</u> containing the current I and B

4. One **Tesla:** is defined as the magnetic flux density if a force per unit length of <u>one newton per metre</u> acts on a current of <u>one ampere</u> in a <u>straight wire</u> perpendicular to the magnetic field {3 m}
   {NOT: ....a force of one newton acts on a current of one ampere in a wire of length <u>one metre</u> which is perpendicular to the magnetic field. (N09P3Q2b) }

5. Must know how to solve problems involving the rotational equilibrium of a **current balance**.

6. Must know how to explain the forces between current-carrying conductors & predict their direction using **Fleming's Left Hand Rule** & **Right-hand Grip rule.** {an explanation based on "like currents attract, unlike currents repel" is NOT acceptable!}

7. Force acting on a moving charge: $F = B\,Q\,v \sin\theta$ {θ: angle between B and v}

8. Possible Paths of a moving charged particle in a magnetic field:
- If $\theta = 0$ or 180^0: undeflected
- If $\theta = 90^0$: circular (or arc of a circle)
- If θ is not 0, 90^0 or 180^0: helical.

{In all 3 cases, the speed remains unchanged as F_B is always perpendicular to v.}
If velocity of particle changes, path could be a spiral. (see tutorial Q13)

9. **Crossed-fields in Velocity Selector:** A setup whereby an E-field and a B-field are perpendicular to each other such that they exert equal & opposite forces on a moving charge & hence causes no deflection of the particle.

i.e. Magnetic Force = Electric Force (same magnitude but in opposite directions)

$$B\,q\,v = q\,E$$

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

Thus, only particles with speed = $\frac{E}{B}$ emerge from the cross-fields undeflected.
For particles with speed > $\frac{E}{B}$, Magnetic Force > Electric Force (deflect in general direction of F_B)
For particles with speed < $\frac{E}{B}$, Magnetic Force < Electric Force (deflect in general direction of F_E)

Topic 16: Electromagnetic Induction

1.

Magnetic flux, ϕ	The product of the magnetic flux density B and the area A *perpendicular* to the field through which the field is passing {also the product of the component of B which is $\perp$ to the plane of coil & the area A of coil} Scalar; S.I. unit : weber (Wb).	$\phi = B\,A$
Magnetic flux linkage, $N\phi$	The product of the magnetic flux passing through a coil and the number of turns of the coil. {In N09P2Q6, unit was Wb- turns}	$\Phi = N\,\phi = N\,B\,A$

2. The **weber** (Wb) is defined as the magnetic flux if a flux density of one tesla passes perpendicularly through an area of one square metre. i.e. 1 Wb = 1 T m^{-2}

3. **Electromagnetic induction** refers to the phenomenon whereby an e.m.f. is induced when the magnetic flux linking a conductor changes.

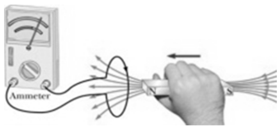
4.

Faraday's Law:	The magnitude of e.m.f. induced in a coil is directly proportional to the rate of <u>change</u> of *magnetic flux* linking or cutting the coil.	$\lvert E \rvert = \frac{d(NBA)}{dt}$
Lenz's Law:	The direction of the induced e.m.f. is such that <u>its effects</u> oppose the <u>change which causes it</u>. {The direction of the induced e.m.f. is such that it gives rise to an induced current whose magnetic field opposes the **change** in flux.}	Negative sign in $E = -\frac{d(N\phi)}{dt}$ denotes Lenz's law

- Negative sign must be taken into account <u>when sketching graph</u> of e.m.f. from gradient of flux-time graph. {N08P1Q33}

5. Explain how Lenz's Law is an example of the law of conservation of energy:
- As the external agent brings the magnet towards the coil, by Lenz's law, a <u>current is induced</u> in such a direction that the coil opposes, i.e. repels the approaching magnet.
- Consequently, <u>work has to be done</u> by the external agent to overcome this opposition {the repulsive force}, and
- It is this work done which is the source of the <u>electrical energy</u> {Not: induced e.m.f. }

{Illustrate with following diagram}



6. Must know how to deduce direction of induced current when a flux change occurs.
Use the <u>4-step guide</u> in applying Faraday's and Lenz's Laws:
1. Identify the change in magnetic flux or flux linkage
2. Apply Faraday's Law to show that e.m.f. is induced
3. Apply Lenz's Law to determine direction of induced e.m.f.
4. Apply Right Hand Grip Rule or Fleming's Left Hand Rule to determine direction of induced e.m.f. /induced current

7. For a straight conductor "cutting across" a B-field:

e.m.f. $E = BLv$ (note that B and v must be perpendicular to each other)

8. For a coil rotating in a B-field, with angular frequency ω:

	Expressions for Φ and E	
Initial condition (at t = 0)	**Φ**	**$E = -\frac{d\Phi}{dt}$**
Coil <u>parallel</u> to Field	$\Phi = N\phi = NBA\sin(\omega t)$	$E = -NBA\omega\cos(\omega t)$
Coil <u>perpendicular</u> to Field	$\Phi = N\phi = NBA\cos(\omega t)$	$E = NBA\omega\sin(\omega t)$

Thus, graphs of E - t & ϕ - t , for the <u>rotating coil</u> have a <u>phase difference of 90^0</u>.

9. For a Rotating Disc:
E.m.f. induced between centre & any pt on rim, $E = B\,\pi r^2 f$ {N2011 P1Q32}

10. For a coil moving through a magnetic field region:

Position of coil	Magnetic Flux Linkage	Induced e.m.f.
Outside field	0	0
Entering field	Increases uniformly (area increases at constant rate)	$-NBLv$ (negative and constant)
Completely inside field	$NBLx$ (Constant area)	0
Leaving field	Decreases uniformly (area decreases at constant rate)	$+NBLv$ (positive and constant)
Outside field	0	0

11. Eddy currents can dissipate energy in the material as heat and are sources of energy losses in transformers, electrical motors and generators. To reduce eddy currents, the bulk piece of metal is laminated.

Topic 17: Alternating Currents

1. **Instantaneous current**: $I = I_0 \sin\omega t$ or $I_0 \cos\omega t$, {Similarly, $V = V_0 \sin\omega t$ or $V_0 \cos\omega t$}

2. **Root-mean-square current of an a.c.:** the magnitude of the steady direct current that produces the same average heating effect {i.e. $I^2 R$} as the alternating current in a given resistor.
{OR, the rms value is the square root of the averaged value of a squared alternating voltage.}

$$I_{rms} = \frac{I_0}{\sqrt{2}}, \quad V_{rms} = \frac{V_0}{\sqrt{2}}$$, (for sinusoidal ac only, not for square AC (N08P1Q34))

$$I_{rms} = \sqrt{\frac{\text{Area of } I^2 \text{ vs time graph}}{\text{time}}};$$ (for square/other AC)

$$V_{rms} = \sqrt{\frac{\text{Area of } V^2 \text{ vs time graph}}{\text{time}}}$$

3. **Relationship between Peak, & rms values of p.d. & current:** $V_0 = I_0 R$, $V_{rms} = I_{rms} R$

4. **Mean/Ave Power** $P_{ave} = I_{rms}^2 R = \frac{V_{rms}^2}{R} = I_{rms} V_{rms}$

= ½ x maximum instantaneous power = ½ $I_0 V_0$ {for sinusoidal AC only}

5. **Max (Instantaneous) Power** $P_{max} = I_0^2 R = \frac{V_o^2}{R} = I_0 V_0$

6. Need to explain the use of a single diode for **half-wave rectification**. {See another treatment in terms of the effect on depletion region of p-n junction when in forward & reverse bias-Topic 19}

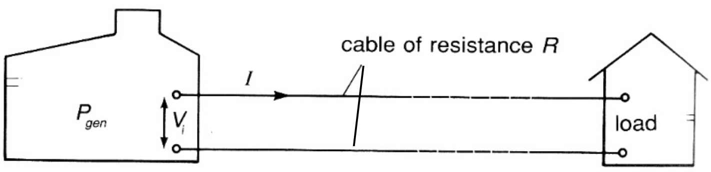
7. I_{rms} for half sinusoidal ac = $\frac{I_0}{2}$; V_{rms} for half half sinusoidal ac = $\frac{V_0}{2}$.

8. **Ideal transformer:** $V_p I_p = V_s I_s$ {Mean power in the primary coil = Mean power in the secondary coil}

$$\frac{V_s}{V_p} = \frac{N_s}{N_p} = \frac{I_p}{I_s}$$

{Values of I & V may be either rms or peak but not instantaneous values; $\frac{N_s}{N_p}$: **turns ratio**}

9. **Power Loss during Transmission of Electrical Power**



Power generated at power station, $P_{gen} = V_i I$, where I: current in the transmission
V_i: voltage at which power is transmitted

Power loss in transmission cables, $P_L = I^2 R_C = (\frac{P_{gen}}{V_i})^2 R_C$ where R_C = cable resistance

Thus to reduce power loss for a given amount of power generated, electricity is transmitted at <u>high voltage</u> (i.e. low current) by stepping up the a.c. voltage using a transformer. {V_i is <u>NOT</u> the p.d. across the cables.}

<u>Topic 18: Quantum Physics</u>

1. A **photon** is a discrete packet {or quantum} of energy of an electromagnetic radiation/wave.

Energy of a photon, $\boxed{E = h f = h c / \lambda}$ where h: Planck's constant

- $\lambda_{violet} \approx 4 \times 10^{-7}$ m; $\lambda_{red} \approx 7 \times 10^{-7}$ m {N2007P1Q34: need to recall these 2 values}

2. **Power** of EM radiation P = Rate of incidence of photon x Energy of a photon = $\left(\frac{n}{t}\right)\frac{hc}{\lambda}$

3. **Photoelectric effect** refers to the <u>emission of electrons from a (cold) metal surface</u> when <u>electromagnetic (EM) radiation</u> of <u>sufficiently high frequency</u> falls on it.

4 Major Observations:

(a) No electrons are emitted if the frequency of the EM radiation is below a minimum frequency {called the **threshold frequency f_o**}, regardless of the intensity of the radiation.

(b) Rate of electron emission {i.e. **photoelectric current**} is proportional to the EM radiation intensity.

(c) The **max KE** of photo-electrons depends only on the frequency and the metal used {workfunction, ϕ}, not the intensity.
{Emitted electrons have a *range of kinetic energy*, ranging from zero to a certain maximum value}

(d) Emission of electrons begins instantaneously {i.e. no time lag between emission & illumination} even if the intensity is low.

NB: (a), (c) & (d) cannot be explained by Classical Wave Theory of Light; instead they provide <u>evidence for the particulate {particle-like} nature of EM radiation</u>.

Failure of the Classical Wave Theory to explain PE:
Explanation for how photoelectric effect provides evidence for the particulate nature of EM radiation: {N07 P3}
{Consider the observations (a), (c) & (d). *Use <u>any 2</u> of the 3 contradictions to describe how they provide evidence that EM radiation has a particle-like nature as illustrated below.}*

1. According to the "Particle Theory of Light", EM radiation consists of a stream of particles/ photons/ discrete energy packets, each of energy hf.
2. An electron is ejected when a <u>single</u> photon of sufficiently high frequency, transfers <u>ALL</u> its energy in a discrete packet to the electron.

3. According to the equation, $hf - \phi = ½ m_e v_{max}^2$, if the energy of a photon hf < the minimum energy required for emission (ϕ), no emission can take place, no matter how intense the light may be. {Explains observation (a)}
4. This also explains why, (even at very low intensities), as long as $hf > \phi$, emission takes place without a time delay between illumination of the metal & ejection of electrons. {Explains observation(d)}

4. Photoelectric equation:
Energy of a photon = Work function + Max. KE of ejected electrons *{ word equation }*

$$hf = \phi + ½ m_e v^2_{max}$$

5. Threshold frequency f_o is the minimum frequency of the EM radiation required to eject an electron from a metal surface.

6. Work function ϕ of a metal is the minimum energy required to eject an electron from a metal surface. {This energy is necessary because the electrons are held back by the attractive forces of the positive nuclei in the metal.}

Thus, $\phi = h f_0 = hc/\lambda_0$ where f_0: threshold frequency.
λ_0 : threshold wavelength

7. Stopping potential V_s is the minimum negative potential required to stop the fastest electron {& thus, ALL the electrons} from arriving at the collector plate.

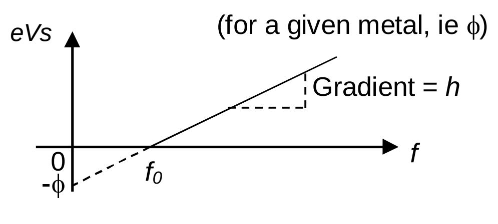
8. Why do photoelectrons have a *range* of KE?
{Shouldn't they all have the same KE since hf - ϕ = a constant? }
Ans: electrons below the surface lose some KE on their way to the surface if and when they collide with the metallic lattice; they do not ALL experience the same loss in KE during such collisions before they are emitted.

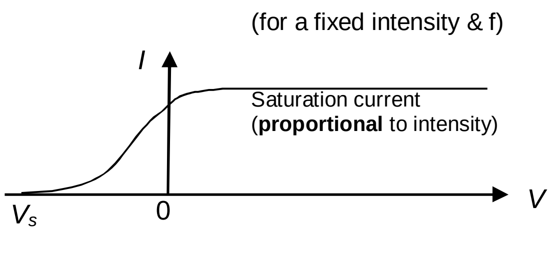
Maximum KE of electrons, $½ m_e v^2_{max} = eV_s$ {in mag}, where V_s : stopping potential

$$h f - \phi = eV_s$$

NB: $KE_{max} = eV_s$ **only** if velocity of photoelectrons is perpendicular to plane of emitter; otherwise $½ m_e(v_{max} \sin\theta)^2 = eV_s$ (Refer H2 BT 2 2013 P3 Q6c)

9. From $eV_s = h f - \phi$,





- If only intensity doubles, the saturation current doubles (V_s: no change)
- If only frequency is increased, magnitude of V_s increases, no change to saturation current.
- Why does the current *not* continue to increase beyond its "saturation value" when the p.d. V is increased?
  Ans: For that given light intensity, all electrons ejected by the photons are already successfully collected by the collector electrode even for a low positive voltage applied {i.e. none has

managed to "escape"}; thus increasing to higher positive *V* values will make no difference to the current (i.e. number of electrons emitted and collected).

- What does the sloping section of the graph for negative values of p.d. represent?
  Ans: It denotes the fact that the electrons are emitted with a range of KE.

10. Intensity = $\frac{Power}{Illumintated\ Area} = \frac{E_{photons}}{A.t} = \frac{n\,hf}{At}$

$\Rightarrow$ Rate of incidence (of photons) $= \frac{n}{t} = \frac{Intensity\ x\ Area}{hf}$

{In the context of photoelectric effect questions "intensity" is to be understood as a measure of the rate of arrival of the photons at the metal, & not the energy of an individual photon.

11. Rate of emission of electrons = $\frac{N}{t} = \frac{I}{e}$ {from $I = \frac{Q}{t} = \frac{Ne}{t}$}

$Current\ I \propto Intensity$

$\frac{N}{t} \propto \frac{n}{t}$

12. Explain why rate of emission of electrons << rate of incidence of photons:

1. Not every photon would collide with & emit an electron; most are reflected by the metal or miss hitting any electron.
2. On the way out to the metal surface, an electron may lose some kinetic energy to ions and other electrons it encounters along the way. This energy loss prevents it from overcoming the work function & so such electrons are absorbed by the metal.

13. 1 eV = (1.6 x 10^{-19} C) x (1 V) = 1.6 x 10^{-19} J {Using $W = qV$}

14. Wave-Particle Duality Concept
refers to the idea that light and matter {such as electrons} have both wave & particle properties.

Interference and diffraction provide evidence for the wave nature of E.M. radiation.
Photoelectric effect provides evidence for the particulate nature of E.M. radiation.
These evidences led to the concept of the wave-particle duality of light.
Electron diffraction provides evidence that matter /particles have also a wave nature & thus, have a dual nature.

15. de Broglie wavelength of a particle {i.e. for "matter waves"}, $\lambda = \frac{h}{mv} = \frac{h}{p}$

16. Energy Levels: refer to the possible energy values an electron can have without it radiating any energy. (H1 2008P2Q4a).

- Energy levels are discrete/ quantised {i.e. can only have certain energy values}.
- Energy difference between successive energy levels, ΔE, decreases as we move from ground state upwards.

17. An **"isolated" atom** refers to an atom whose nearest neighbouring atom is sufficiently far apart that the inter-atomic force between them is negligible. Eg. a low density monatomic gas (i.e. a gas at *low* pressure).

18. **Ionisation energy** is the minimum energy required to remove an unexcited electron from the atom (from ground state to the level n = ∞, where $E_\infty = 0$)

19. Excitation of an atom via:

1. bombarding particle (eg. another electron): only if the incident electron has KE $\geq \Delta E$ (difference in energy levels)
2. absorption of an incident photon: only if energy of the photon is exactly equal to ΔE

20. Energy of the absorbed (or emitted) photon is = difference in energy between these 2 energy levels/states: $\Delta E = \left|E_f - E_i\right| = hf = \frac{hc}{\lambda}$

21. **Emission line spectrum:** a series of discrete/ separate bright lines of definite wavelength /frequency on a dark background, produced by electron transitions within an atom from higher to lower energy levels and emitting photons.

22. **Absorption line spectrum:** a continuous bright spectrum crossed by "dark" lines due to some missing frequencies.
It is produced when white light passes through a 'cool' gas. Atoms/ electrons of the cool gas absorb photons of certain frequencies from the white light source, and get excited to a higher energy level which are then quickly re-emitted uniformly in all directions.

Explain how existence of electron energy levels in atoms gives rise to line spectra {N03P3Q6, 4 m}

- Energy levels are discrete.
- During a downward transition, a photon is emitted.
- Frequency of photon, $f = \frac{E_i - E_f}{h}$
- Since E_i & E_f can only have discrete values, the frequencies are also discrete and so a line {rather than a continuous} spectrum is produced. {No need to mention spectrometer}

23. **Significance of Line Spectra**:

- The fact that the lines are separated/ discrete is experimental evidence for the existence of discrete or "quantized" energy levels in the atoms.
- Because all isolated atoms of any particular element have the same characteristic set of energy levels, each element produces a unique line spectrum which may be used to identify the element (source of the radiation).

24. **Characteristic X-rays**: Origin:

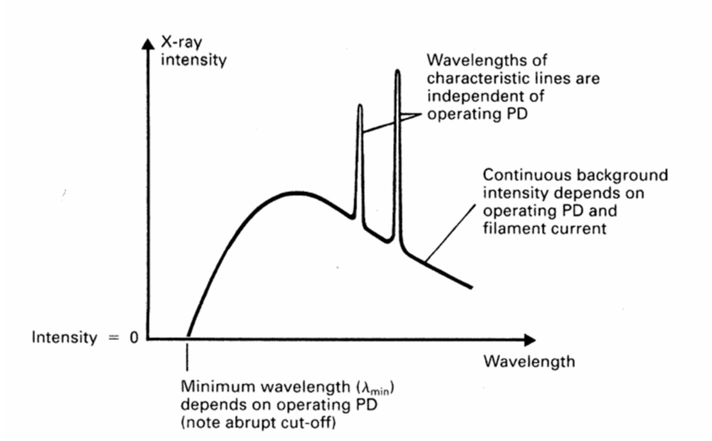
- A high-energy electron colliding with a target metal atom can knock an electron out of an inner shell of this target metal.
- Another electron (of target atom) from a higher energy state drops down to fill the vacancy,
- thus emitting an X-ray with a specific wavelength, which is determined by the discrete energy levels (which are characteristic of the target metal).

Continuous X-ray Spectrum (Braking Radiation/Bremsstrahlung): Origin:

- X-rays produced when fast electrons are suddenly decelerated upon collision with atoms of the metal target.
- The frequencies of emitted X-rays have a continuous range because the deceleration can occur in a nearly infinite number of different ways &

- hence the energies lost by electrons vary from one collision to another across a continuous range of values (hence spectrum).
  {The freq of the X-ray is determined by the loss in KE of the decelerated electron.}

25. X-ray spectrum:



- **Minimum λ of continuous spectrum, λ_{min} :** given by $\frac{hc}{\lambda_{min}} = e\,V_a$
  V_a: accelerating p.d. of x-ray tube
  {λ_{min} is the wavelength of the x-ray photon emitted when a bombarding electron loses ALL its KE in a single collision with the target atom.
  Note: A related misconception is to apply $\lambda = \frac{h}{m_e v}$ to determine λ_{min} }

26. Heisenberg's Uncertainty Principle:
If a measurement of the position of a particle is made with uncertainty Δx and a simultaneous measurement of its momentum is made with uncertainty Δp, the product of these 2 uncertainties can never be smaller than $h / 4\pi$.

i.e. $\Delta x\,\Delta p \geq \frac{h}{4\pi}$ ie. $m_e\,\Delta v\,\Delta x \geq \frac{h}{4\pi}$

A reasonable estimate of the (maximum) Δx = the full length of the "container".

Similarly $\Delta E\,\Delta t \geq \frac{h}{4\pi}$

which tells us that the energy E of a particle can be uncertain by an amount ΔE for a time Δt.
{Application: energy of an excited electron where Δt is the lifetime of that excited state.}

27. A particle can be described by a **wave function Ψ** where the square of the amplitude of wave function, **$|\Psi|^2$,** gives the probability of finding the particle at that point.

28. Potential barrier:
a region where a particle would experience a force which opposes it from entering into that region.

29. Quantum tunnelling:
A quantum-mechanical phenomenon whereby a particle goes through a potential barrier even though it does not have enough energy to overcome it. This can happen because, due to the wave

nature of a particle, there is a non-zero probability that the particle is able to penetrate the potential barrier.

30. Scanning tunnelling microscope:
involves passing electrons from the tip of a probe through a vacuum [potential barrier] to a material that is to be scanned.

- Quantum tunnelling allows electrons to overcome the potential barrier between the tip & material.
- Magnitude of tunnelling current is very sensitive to the distance between the tip and the material surface {due to the exponential function in the transmission coefficient}
- There are two methods to obtain images of the surface of the material:

  (1) Maintain a constant tunnelling current and measure the (vertical) height of the tip.
  (2) Maintain the tip at constant height and measure the tunnelling current.

  (A feedback arrangement adjusts the vertical height of the tip to keep the tunnelling current constant as the tip is scanned over the surface {for method 1}).
- The output of the device provides an image of the surface contour of the material.

31. Transmission coefficient (T): measures the probability of a particle tunnelling through a barrier.

$T \propto e^{-2kd}$ where $k = \sqrt{\frac{8\pi^2 m(U - E)}{h^2}}$ {given in Formula List}

d = the thickness of the barrier in metres,
m = mass of the tunnelling particle in kg
U = the "height" of the potential barrier in J,
E = the energy of the electron in J.{**Not: eV**}
h = the Planck's constant

Reflection coefficient (R): measures the probability that a particle gets reflected by a barrier.
Thus, $T + R = 1$

Topic 19: Lasers & Semiconductors

1. **Spontaneous Emission** refers to the process whereby a photon is emitted by an atom in an excited state of its own accord {ie without being triggered by any outside influence}.

2. **Stimulated Emission** refers to the process whereby an incoming/ external photon causes {or induces/ triggers/ stimulates} another photon of the same frequency, phase (and plane of polarization) to be emitted from an excited atom. The incoming photon is NOT absorbed.

3. **Laser**: a light source that produces a beam of highly coherent and monochromatic photons using the principle of stimulated emission.
4 properties of LASER: high intensity, coherent, highly monochromatic, highly directional.

4. **Metastable state:** an excited state whose lifetime is much longer than the typical lifetime of excited states {about 10^{-8} s}.
A metastable state is essential for laser production because it is required for population inversion to be achieved, which, in turn, is necessary so as to increase the probability of stimulated emissions.

5. **Population inversion:** a situation where there are more atoms in an excited state than in a lower energy state / ground state.

6. **3 Conditions to achieve laser action:**
    1. The system/ laser medium must have atoms with a *metastable* state.
    2. The system must be in a state of *population inversion*.
    3. The emitted photons must be confined in the system long enough to allow them to cause a chain reaction of stimulated emissions from other excited atoms. {3rd bullet: least important of the 3 conditions}

7. An atom emits (& also absorbs) EM radiation/photons only at frequencies that correspond to the energy differences between the energy levels/ allowed energy states: $\Delta E = E_i - E_f = hf = \frac{hc}{\lambda}$

8. Energy {per pulse} = (Number of photons {per pulse}) x Energy of each photon
Power of beam = (No. of photons emitted per unit time) x (Energy of each photon)

9. **Formation of energy bands in a solid/ Band Theory for solids:**
    - Unlike the case of an isolated atom, in a solid, the atoms are very much closer to each other. This allows the electrons from neighbouring atoms to interact with each other.
    - As a result of such interactions, each discrete energy level {that is associated with an isolated atom} is split into sub-levels that are extremely close to one another such that they form an energy band. {In other words, an energy band consists of a very large number of energy levels which are very close together.}

10. **Valence band:** is the highest band of the fully-occupied energy bands.
    - Electrons in the VB are tightly bound to their atoms and are not able to conduct electricity.

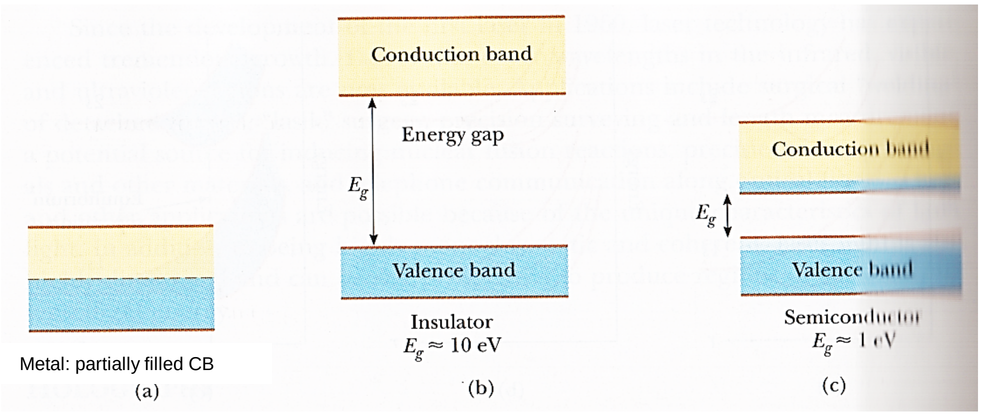
    Conduction band: is the next higher band above the valence band (i.e. the lowest of the not-fully-occupied energy bands).
    - For metals, it is partially-filled ;
    - For insulators & semiconductors at 0 K {ie 'low temp'}, it is empty.
    - In the conduction band, electrons (if any) in this band are free to move between atoms of the solids & become charge carriers/ conduction electrons.

    Energy Gap [Forbidden band]: a region where no state can exist; {it is the energy difference between the conduction & valence bands}

11. **Properties of metals/ conductors, insulators and semi-conductors at 0 K** {i.e. at "low temp"}:

	Metals	**Insulators**	**Semi-conductors**
Conduction Band	Partially filled	Empty (sc is an insulator at zero K)	
Valence Band	Completely occupied		
Energy gap between the bands	NA	Large (≈5-10 eV)	Small (≈1 eV)

12. Band Structures of (a) Metal, (b) Insulator & (c) Intrinsic Semiconductor at normal (ie not zero K) temperature:



13. Explain how band theory accounts for the relative conducting ability of a metal, intrinsic semiconductor at normal temperature & an insulator:

- For a **(good) conductor (i.e. a metal)**, when an electric field is applied, electrons in the partially-filled conduction band (Fig a) can very easily gain energy from the field to "jump" to unfilled energy states since they are nearby.
- The ease at which these electrons may move to a nearby unfilled/ unoccupied energy state, plus the fact that there is a high number density of free electrons make metals very good electrical conductors**.**
- For an **insulator**, the conduction band is completely unoccupied by electrons; the valence band is completely occupied by electrons; and the energy gap between the two bands is very large (Fig b).
- Since the conduction band for an insulator is completely empty, and a lot of energy is required to excite the electrons from the valence band to the conduction band across the wide energy gap, when an electric field is applied, no conduction of electricity occurs. {Thus, insulators make poor conductors of electricity.}
- For ***intrinsic semi-conductors***, the energy gap between the two bands is relatively small {compared to insulator}
- As such, even at room temp, some electrons in the valence band gain enough energy by thermal excitation to jump to the unfilled energy states in the conduction band, leaving vacant energy states in the valence band known as holes (Fig c). When an electric field is applied, the electrons (which have jumped into the conduction band) and holes (in the valence band) act as *negative* and *positive* charge carriers respectively and conduct electricity.
  {Thus, for *intrinsic* semiconductors, the ability to conduct vary with temperature {or even light, as light can cause photo-excitation}.

14. A **hole** is a vacancy in the semiconductor lattice left behind by a bound electron (in the VB) which has become a free electron (in the CB). It is a region of positive charge.

15. Doping: Adding impurity atoms to a semiconductor to modify the number and type of charge carriers.

- **n-type** doping increases the no. of free {NOT: valence } electrons;
- **p-type** doping increases the no. of holes.
- Note that even with a very small increase in the dopants, the electrical resistivity of an extrinsic semiconductor decreases significantly, because to begin with, the number of charge carriers of the intrinsic semiconductor {before doping} is typically very small.

16. Explain why electrical resistance of an intrinsic semiconductor material decreases as its temperature rises. {N08P2Q5, 4m}

(Based on the band theory, at zero K, an intrinsic semiconductor has a completely filled valence band & an empty conduction band with a small energy gap in between. Hence there are no charge carriers & the resistance is high.)

- When temperature rises, electrons in the VB receive thermal energy to enter into the CB leaving holes in the VB. [1]
- Electrons in the CB & holes in the VB are mobile charge carriers & can contribute to current [1]
- Increasing the number of charge carriers tends to lower resistance. [1]
- As temp rises, lattice vibrations increases, which tends to increase resistance, but its effect is outweighed by the increase in number of charge carriers. {N2012 P3Q5a} [1]

17. 2 Differences between p-type silicon & n-type silicon:

- In n-type Si, the majority charge carrier is the electron, its minority charge carrier is the hole. For p-type Si, the situation is reversed.
- In n-type Si, the dopants are typically pentavalent atoms (valency = 5); in p-type Si, the dopants are typically trivalent atoms (valency =3).

18. Origin of **Depletion region**: (N20O7 P2 Q5)

- As soon as an n-type material and a p-type material come into contact, some free electrons from the n-type material diffuse towards the p-type material because of the *higher concentration* of mobile electrons in the former,
- leaving behind/ "uncovering" the immobile/ fixed positively-charged donor ions.
- Similarly, holes diffuse from the p-type material towards the n-type material because of the *higher concentration* of holes in the p-type material,
- also leaving behind a region of immobile negatively-charged acceptor ions (**draw** Fig 17a of Lect Notes).
- When a free electron and a hole meet, they **recombine** (the free electron becomes a bound electron and the hole ceases to exist), and so, the region around the junction becomes depleted of mobile electrons and holes (Draw Fig 17b of Lect Notes).

19. Explain How a **p-n Junction diode can act as a rectifier:**

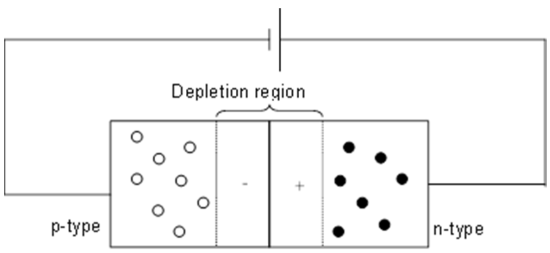


Fig. 1

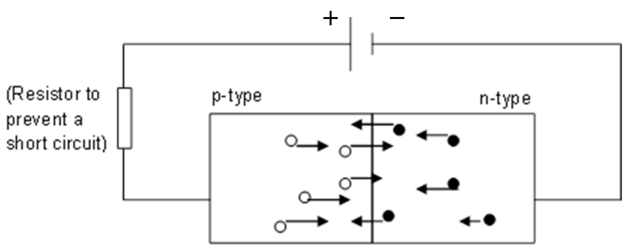


Fig. 2

- During the half-cycle when the p-n junction is in reverse bias as shown in Fig. 1, [1]
- the holes in the p-type semiconductor are pulled towards the negative terminal of the a.c. source, leaving behind more negatively-charged ions near the junction, while the free electrons in the n-type semiconductor are pulled towards the positive terminal, leaving behind more positively-charged ions near the junction. [1]

- This results in the widening of the depletion region and an increase in height of the potential barrier/ contact p.d., thus preventing any current flow. {Note that recombination is not involved} [1]
- For the next half-cycle when the p-n junction is in forward bias (Fig. 2), the external field opposes the contact pd. [1]
- The depletion layer will become narrower & the height of the potential barrier will decrease ; thus allowing current to flow readily. [1]

Topic 20: Nuclear Physics

1. Describe the experimental evidence for a small charged nucleus in an atom (N08P3Q7a, 4m)
   - Most of the α-particles which passed through the metal foil were deflected by very small angles,
   - A very small proportion was deflected by more than 90^0, some of these approaching 180^0.
   - From these observations, it can be deduced that: the nucleus occupies only a small proportion of the available space {i.e. the atom is mostly empty space}
   - & that it is positively charged since the positively-charged α-particles are repelled/ deflected.

2. **Nucleon:** a particle within the nucleus; can be either a proton or a neutron.
   Nuclide: an atom with a particular number of protons and a particular number of neutrons.
   Proton number {atomic number}: Number of protons in an atom.
   Nucleon number {mass number}: Sum of number of protons and neutrons in an atom.
   Isotopes: atoms with the same proton number, but different number of neutrons in the nuclei {N2011P2Q5a(i)}

3. Energy & Mass are equivalent: $E = m c^2$ → $\Delta E = (\Delta m)\, c^2$

4. **Nuclear Binding Energy:** energy that must be supplied to completely separate the nucleus into its individual particles.
   or: the energy released {not: *lost*} when a nucleus is formed from its constituent nucleons.

   B.E. per nucleon is a measure of the stability of the nucleus.

5. **Mass defect {**or **excess}**:
   The difference in mass between a nucleus and the total mass of its individual nucleons
   $= Zm_p + (A-Z)m_n$ – Mass of nucleus

   Thus, *Binding Energy = Mass Defect × c²*

   In both nuclear fusion and fission, products have higher B.E. per nucleon {due to shape of BE per nucleon vs nucleon number graph}, energy is released {not: *lost*} and hence products are more stable.

6. **Energy released** = total B.E. after reaction (of products) - total B.E. before reaction (of reactants)

7. **Principle of conservation of energy-mass:**
   Total energy-mass before reaction = Total energy-mass after reaction

   i.e. $\sum (mc^2 + \frac{1}{2} mv^2)_{reactants} = \sum (mc^2 + \frac{1}{2} mv^2)_{products} + hf$ {if any}

8. Energy released in nuclear reaction = Δmc^2

= (total rest mass before reaction – total rest mass after reaction) $\times c^2$

9. Nuclear fusion: Process where 2 light nuclei are combined to produce a heavier nucleus.

10. Nuclear fission: Process where a heavy nucleus disintegrates into 2 lighter nuclei with the release of energy. Typically the fission fragments have approximately the *same mass* and neutrons are emitted.

Note: the total masses after the reaction are less than the total masses before. The amount of energy released (mostly in the form of kinetic energy of the products) is the energy equivalent of the "missing mass", which can be calculated by E = m c^2.

11. Spontaneous reactions: when rest mass energy of reactants > rest mass energy of products.

12. Radioactivity is the spontaneous and random decay of an unstable nucleus, with the emission of an *alpha* or *beta* particle, and usually accompanied by the emission of a *gamma* ray photon.

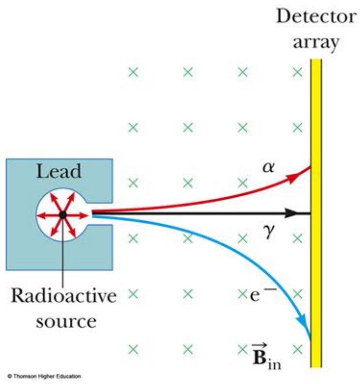
Spontaneous:	The decay occurs without the need of an external trigger & is not affected by factors outside the nucleus such as temperature, pressure, etc. {must give at least 1 example}
Random:	It cannot be predicted when the next emission will occur, even though the probability of decay per unit time of a nucleus is constant. {Evidence: the fluctuation in count-rate}

13. Nature of α, β & γ

	Alpha	Beta	Gamma
Notation	${}^4_2\alpha$ or ${}^4_2$He	${}^{0}_{-1}\beta$ or ${}^{0}_{-1}$e	γ
Charge	+2e	-e	No charge
Mass	4 u	≈1/2000 u	Massless
Nature	Particle	Particle	EM radiation
Relative ionising ability	Strong	Weak	Very weak
Penetrating ability (For Skill A)	Stopped by a few cm of air at stp or a thin sheet of paper	Stopped by a few mm of aluminium or ≈ 1 m of air at stp	Stopped by a few cm of lead or 1 m of concrete

14. To distinguish the three forms of radiation, radiation from a radioactive sample is directed into a region with a magnetic field.

1. the radiation of the undeflected beam (γ-ray) carries no charge,
2. the component deflected upward contains positively-charged particles (α-particles) and
3. the component deflected downward contains negatively-charged particles (β-particles).



15. Decay law: $\frac{dN}{dt} = -\lambda N$, where N = number of undecayed [active] nuclei at that instant;

$N = N_0 e^{-\lambda t}$; $A = A_0 e^{-\lambda t}$; $C = C_0 e^{-\lambda t}$ {in List of Formulae}

16. Decay constant λ : defined as the probability of decay of a nucleus <u>per unit time</u>, or, the fraction of the total no. of undecayed nuclei which will decay per unit time.

17. Activity, A : the rate at which the nuclei are disintegrating.

i.e. $A = \frac{dN}{dt} = \lambda N$

$\Rightarrow A_0 = \lambda N_0$

S.I. unit of A: becquerel (Bq); where 1 Bq = 1 disintegration per second.
or simply *second*$^{-1}$, s^{-1}

18. Count-rate, C : number of counts per unit time recorded by a radiation detector (eg a GM tube connected to a ratemeter).
In general, count-rate is proportional (not equal) to the activity.

19. Half-life, $t_{1/2}$: is defined as the <u>average</u> time taken for <u>half</u> the <u>number</u> {not: mass or amount} of undecayed nuclei in the sample to disintegrate,
or, the <u>average</u> time taken for the <u>activity</u> to be halved.

i.e. $t_{½} = \frac{\ln 2}{\lambda}$ {in List of Formulae}

20. $A = \frac{\ln 2}{t_{1/2}} \times N$

Thus, 2 factors which determine Activity, A of a given sample are:
1. half-life (or λ)
2. number of undecayed nuclei N

21. $\frac{N}{N_o} = \left(\frac{1}{2}\right)^n$; $\frac{A}{A_o} = \left(\frac{1}{2}\right)^n$; $\frac{C}{C_o} = \left(\frac{1}{2}\right)^n$ where n = number of half-lives elapsed.

22. Number of undecayed nuclei $\propto$ Mass of sample

Number of nuclei in sample = $\frac{\text{Sample Mass}}{\text{Mass of 1 mol}} \times N_A$

where,
mass of 1 mol of nuclide = nucleon no. {or relative atomic mass} <u>expressed in grams</u> {NOT: in kg}
{Thus for eg, mass of 1 mole of U-235 = 235 g = 235 x 10^{-3} kg, NOT: 235 kg}

23. **Background radiation** refers to radiation from sources other than the source of interest.

True count rate = measured count rate – background count rate

24. Recall of $KE = \frac{p^2}{2m}$ to solve problems involving conservation of momentum in radioactive decay is allowed {N2010 P3 Q8 (a(ii)}. Note however it is <u>only applicable if there are only TWO products after decay,</u> e.g. a daughter nucleus + one of either α, β or γ.

25. Ionising radiation may damage or destroy biologically important molecules directly or indirectly.

(a) If radiation interacts with the atoms of the DNA molecule directly → direct effect. Such an interaction may damage or destroy the cell by "direct" interference with its life-sustaining system.

(b) Harm caused through chemical changes to the surrounding medium of the cells, which is mainly water. → indirect effect.