IB Physics Notes

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Contents

1 Measurements and Uncertainties

1.1 Measurements in Physics

1.1.1 Fundamental and derived SI Units

SI Units: The international system of units.

Fundamental Units: These are the 7 basic units all other SI units are made up of. They are:

Name	**Symbol**	**Quantity**
Meter	m	distance
Kilogram	kg	mass
Second	s	time
Ampere	A	electric current
Kelvin	K	temperature
Mole	mol	substance
Candela	cd	luminous intensity

Derived units: These are all the units derived from the fundamental ones. For example, ms^{-1} for speed.

1.1.2 Scientific Notation and metric multipliers

Numbers in the form $a \times 10^b$ are said to be in scientific notation form. Here, b must be a positive or negative integer, and $1 \leq a \leq 10$.

Metric multipliers are used to express quantities using powers of 10. These can be added as prefixes to basic units. Common ones are:

Power	**Prefix**	**Symbol**
10^{-9}	nano-	n
10^{-6}	micro-	μ
10^{-3}	milli-	m
10^{-2}	centi-	c
10^{-1}	deci-	d
10^{3}	kilo-	k
10^{6}	mega-	M
10^{9}	giga-	G

More can be found in the data booklet.

Significant figues: The number of digits used to express a quantity/number. It tells us how precisely we know that number.

Rules for significant figures:

- For integers, all digits count **except** leading and trailing zeros.
- For decimals, all digits count **except** leading zeros.
- For scientific notation, the number of significant figures in a are used.
- For multiplication or division, the least number of significant figures must be kept in the result.
- For addition or subtraction, the least number of decimal places must be kept in the result.

(leading - zeros in the front, trailing - zeros at the end)

1.1.3 Orders of Magnitude

Expressing a quantity as a power of 10 is called the order of magnitude for that quantity. For example, the mass of the Milky Way galaxy has an order of magnitude of 10^{41}.

1.1.4 Estimation

Estimation.

1.2 Uncertainties and Errors

1.2.1 Random and Systematic Errors

Random error: Unbiased uncertainty due to random fluctuations in measurements. Also includes reading uncertainties (uncertainty due to precision of instruments).

These cannot be eliminated but can be minimized by, for example, doing multiple trials of an experiment and taking the average of recorded values.

Systematic error: Biased uncertainty due to error in methodology or broken instrument.

1.2.2 Absolute, fractional and percentage uncertainties

- Absolute: actual uncertainty in a measurement, expressed using the relevant units. For digital instruments, it is the least count. For analog, it is half of the least count.
- Fractional: ratio of absolute uncertainty to the measurement value.
- Percentage: fractional uncertainty as a percentage.

(Least count: smallest value that can be measured with that instrument)

Some rules for uncertainties in calculation:

- For addition or subtraction, the absolute uncertainty of the result is the sum of the absolute uncertainties in all quantities involved.
- For multiplication or division, the fractional uncertainty of the result is the sum of the fractional uncertainties in all quantities involved.
- For powers and roots, the fractional uncertainty of the result is the fractional uncertainty of the quantity multiplied by the absolute value of the power.

1.2.3 Error bars

Those extra lines on a point to indicate uncertainty range. These are not shown if the error is negligible.

1.2.4 Uncertainty of gradient and intercepts

To get uncertainty of gradient and intercepts, draw a line through the error bars with the maximum gradient, and a line with the minimum gradient. Uncertainty in the gradient is then $(max - min)/2$ and similarly for the intercepts.

1.3 Vectors and Scalars

1.3.1 Vector and scalar quantities

- **Vector:** quantities with magnitude and direction, e.g. velocity and acceleration.
- **Scalar:** quantities with just magnitude, e.g. time, mass.

1.3.2 Combination and Resolution of Vectors

Dealing with vectors is much easier after splitting them into their x and y components, and vectors can also be reconstructed using their components:

- x-component $= A\cos\theta$
- y-component $= A\sin\theta$
- $F = \sqrt{(F_x)^2 + (F_y)^2}$
- $\theta = \arctan\frac{F_y}{F_x}$

Be careful about the angles though, some situations can get confusing.

2 Mechanics

2.1 Motion

2.1.1 Distance and displacement

- Displacement: change in position (vector)
- Distance: length of path followed (scalar)

2.1.2 Speed and velocity

- Velocity: rate of change of displacement (vector)
- Speed: rate of change of distance (scalar)

2.1.3 Acceleration

Rate of change of velocity (vector).

2.1.4 Graphs describing motion

- position/time graph: the slope gives the velocity; the area under the curve gives no useful quantity.
- velocity/time graph: the slope gives acceleration; the area under the curve gives displacement.
- acceleration/time graph: the slope gives no useful quantity (we're not interested in jerks); the area under the curve gives the velocity.

2.1.5 Equations of motion for uniform acceleration

- Uniform motion: constant velocity.
- Uniform acceleration: constant acceleration.

For uniform acceleration *only*, the following equations can be used:

$$v = u + at$$
$$\Delta s = ut + \frac{1}{2}at^2$$
$$\Delta s = \left(\frac{u+v}{2}\right)t$$
$$v^2 = u^2 + 2a\Delta s$$

Where v is final velocity, u is initial velocity, s is position (Δs is displacement), t is time and a is acceleration.

2.1.6 Projectile Motion

A **projectile** is a body under the influence of only gravity, and no other force.

Since only the downwards force of gravity is acting upon it, only the vertical component of the acceleration (and velocity) is affected. There is no acceleration along the horizontal axis, and the velocity along the horizontal axis remains constant.

Use the equations of motion and vector resolution to solve problems about projectile motion.

2.1.7 Fluid Resistance and Terminal Speed

Fluid resistance: Resistive force experienced when a body moves through a fluid (gas or liquid). For small speeds, $F = kv$ and for high speeds, $F = kv^2$.

Terminal speed: As the fluid resistance force becomes larger, it eventually equals the object's weight. The forces cancel out, acceleration becomes 0 and the body moves at constant speed, which is known as the terminal speed. It can be found using $mg = kv$.

2.2 Forces

2.2.1 Objects as point particles

By treating a body as a point particle, we can assume that all forces act through it at the same point.

2.2.2 Free-body diagram

To draw a free-body diagram for a chosen body, we treat it as a point particle and draw arrows to represent all forces acting upon it. The arrows must be proportional to the magnitude of the force. Surroundings and other bodies are ignored.

2.2.3 Translational Equilibrium

We say an object is in translational equilibrium when all forces acting on it add up to zero (i.e the net force is zero).

2.2.4 Newton's Laws of Motion

First law: When the net force on a body is zero, the body will move with constant velocity. Also known as the law of inertia.

Second law: The net force on a body of constant mass is proportional to that body's acceleration and is in the same direction as the acceleration. Mathematically: $F = ma$.

Third law: If a body A exerts a force on body B, then body B will exert an equal and opposite force on body A. Mathematically: $F_{ab} = -F_{ba}$.

2.2.5 Solid Friction

Friction is a force that opposes motion.

- Dynamic/Kinetic friction: when there is motion e.g. one body slides over another. This is given by $f_d = \mu_d R$. R is the normal reaction force, μ_d is the coefficient of dynamic friction.
- Static friction: when there is a tendency for motion but not motion itself e.g. a body on a slope has a tendency to slide down, but is kept motionless by friction. The *maximum* force of static friction is given by $f_s = \mu_s R$. R is the normal reaction force, μ_s is the coefficient of static friction.

Other important stuff:

- $\mu_s > \mu_d$ (it takes more force to get an object to start sliding than to keep it sliding).
- Area of contact does not affect frictional force.

- Force of dynamic friction does not depend upon speed of sliding.
- Again, f_s is the *maximum* friction that can develop before an object will start sliding (once it does, the force acting will be dynamic friction).

2.3 Work, energy and power

2.3.1 Kinetic energy

Energy of a particle due to its motion. $E_k = \frac{1}{2}mv^2$.

Work-kinetic energy relation: $W_{net} = \Delta E_k$.

2.3.2 Gravitational Potential Energy

Work done by the moving force in placing a body a height h above its initial position: $E_p = mgh$.

Gravitational potential energy is a conservative force, i.e the work done by gravity is independent of the path followed and depends only on the vertical distance separating the initial and final positions.

2.3.3 Elastic Potential Energy

Hooke's Law: the force F and extension x of a (stretched) spring are directly proportional, i.e $F = kx$.

Work done by the pulling force in stretching a spring by an amount x: $E_p = \frac{1}{2}kx^2$.

2.3.4 Work done as energy transfer

Work done by a force is the product of the force in the direction of the displacement times the distance travelled, i.e $W = Fd\cos\theta$. Unit: joule ($1J = 1Nm$).

Work done by a force is the area under the graph that shows the variation of the magnitude of the force with the distance travelled.

If a system is in contact with surroundings at a different temperature, there will be a transfer of heat, Q. If there is no contact and no temperature difference, then $Q = 0$. If no work is done from outside, then $W = 0$. When $Q + W = 0$, the system is called *isolated* and $\Delta E = 0$.

2.3.5 Power as rate of energy transfer

Power is the rate at which work is performed or the rate at which energy is transferred: $P = \frac{\Delta W}{\Delta t}$. Unit: Watt (W), $1W = 1Js^{-1}$.

Since $W = Fd$, we also have: $P = \frac{F\Delta d}{\Delta t} = Fv$.

2.3.6 Principle of conservation of energy

Energy is neither created nor destroyed. It is only transformed from one form to another. The total amount of energy in the universe is constant.

2.3.7 Efficiency

Ratio of useful output energy/power to actual input of energy/power, i.e $e = \frac{input}{output}$.

2.4 Momentum and Impulse

2.4.1 Newton's second law as rate of change of momentum

Momentum (product of mass and velocity, vector): $p = mv$

Unit: kgms^{-1} or Ns.

Newton's second law in terms of momentum: $F_{net} = \frac{\Delta p}{\Delta t}$ i.e average net force on a system is equal to the rate of change of the momentum of the system.

2.4.2 Impulse and force-time graphs

Re-arranging Newton's second law in terms of momentum gives: $\Delta p = F_{net}\Delta t$. This quantity is known as the impulse.

The larger the value of Δt, the smaller the net force will be, and vice versa.

2.4.3 Conservation of linear momentum

When the net force on a system is zero the momentum does not change, i.e it stays the same. We say it is conserved.

2.4.4 Elastic collisions, inelastic collisions and explosions

- A collision between two objects is elastic when kinetic energy is conserved. It is perfectly elastic when all of the kinetic energy is conserved.
- A collision between two objects is inelastic when kinetic energy is not conserved. It is totally inelastic when all of the kinetic energy is lost.

Momentum also gives another useful formula for kinetic energy: $E_k = \frac{p^2}{2m}$.

3 Thermal Physics

3.1 Thermal concepts

3.1.1 Molecular theory of solids, liquids and gases

Solids, liquids and gases are made of smaller structures: compounds made of molecules, molecules made of atoms and atoms containing nuclei and electrons.

In solids, particles are held together by bonds between them. In liquids these bonds are weaker, and so the particles are able to slide and move around as well as take the shape of the container. In gases the forces are very weak, and so they are able to move around more freely allowing gases to expand as well.

3.1.2 Temperature and absolute temperature

Temperature is (proportional to) the average random kinetic energy of molecules. It is measured in Kelvin. Absolute temperature is the lowest possible temperature i.e 0 K. This is when the molecules have zero kinetic energy.

Thermal equilibrium is when a chosen body and its surroundings (or another body or bodies) reach the same temperature after energy is transferred between them.

Heat is energy that is transferred from one body to another as a result of a difference in temperature.

3.1.3 Internal energy

Internal energy is the total random kinetic energy of the particles of a substance, plus the total inter-particle potential energy of the particles.

The internal energy of a system can change as a result of heat added or taken out and as a result of work performed.

3.1.4 Specific heat capacity

The energy required to increase the temperature of a unit mass of the body by one kelvin: $Q = mc\Delta T$.

3.1.5 Phase change

- melting: solid to liquid
- freezing: liquid to solid
- vaporisation/boiling: liquid to gas
- condensation: gas to liquid

During the process of phase change, there is no change in the temperature of the body (even as heat is being supplied to it).

3.1.6 Specific latent heat

Amount of energy required to change the phase of a unit mass at constant temperature: $Q = mL$. For melting/freezing, it is called the specific latent heat of fusion. For vaporisation/condensation it is called the specific latent heat of vaporisation.

3.2 Modelling a gas

3.2.1 Pressure

Normal force applied per unit area: $p = \frac{F}{A} = \frac{F\cos\theta}{A}$.

Unit: Pa (pascal) or atm (atmosphere, 1.013×10^5 Pa).

3.2.2 Equation of state for an ideal gas

Ideal gas laws:

- Molecules are point particles with negligible volume.
- Molecules obey laws of mechanics.
- No forces between molecules except when they collide.
- Duration of collision is negligible compared to time between collisions.
- Collisions between molecules and molecules and the container walls are elastic.
- Molecules have a range of speeds and move randomly.

A real gas can be approximated by an ideal gas when the density is low.

The state of a gas is determined by the pressure (p), volume (V), temperature (T), and number of moles (n). The relationship between them is given by the equation of state: $pV = RnT$, where R is the gas constant.

It is derived from the following:

- Boyle's Law: $p \propto \frac{1}{V}$ or $pV = constant$.
- Charles' Law: $\frac{V}{T} = constant$.
- Amonton's Law: $\frac{p}{T} = constnat$.

3.2.3 Kinetic model of an ideal gas

The average random kinetic energy of particles is directly proportional to the kelvin temperature: $\bar{E}_k = \frac{3}{2}\frac{R}{N_A}T$. The ratio $\frac{R}{N_A}$ is also called the Boltzmann constant, k_b.

The total random kinetic energy (the internal energy) is given by: $U = \frac{3}{2}Nk_bT$.

3.2.4 Mole, molar mass and the Avogadro constant

One mole of a substance contains as many particles as there are atoms in 12g of carbon-12.

The number of particles in a mole is $N_A = 6.02 \times 10^{23}$ mol^{-1}. This is known as the Avogadro constant.

The number of moles n in a substance with N particles is: $n = \frac{N}{N_A}$.

The atomic mass unit (1 u) is: $\frac{1}{12}$ of the mass of one atom of carbon-12. The mass of one atom of carbon-12 is exactly 12u. The atomic unit mass is given (in grams) by: $u = \frac{1g}{N_A}$.

One mole of a substance is a quantity of the substance that contains a number of particles equal to the Avogadro constant and whose mass in grams is equal to the molar mass of the substance.

3.2.5 Differences between real and ideal gases

A real gas can be modelled as an ideal gas if it has low density.

4 Waves

4.1 Oscillations

4.1.1 Simple harmonic oscillations

A restoring force, which tries to bring the system to its equilibrium position is necessary for oscillations.

Simple harmonic motion is defined by the property: $a \propto -x$, i.e magnitude of the acceleration is proportional to displacement and the direction of the acceleration is towards the equilibrium position.

During these oscillations, $E = E_k + E_p = E_{kmax} = E_{pmax}$.

4.1.2 Time period, frequency, amplitude, displacement, and phase difference

- Time period: time taken to complete one full oscillation.
- Frequency: number of oscillations per second, $f = \frac{1}{T}$.
- Amplitude: maximum displacement from the equilibrium position.
- Displacement: distance from equilibrium position.
- Phase difference: amount by which a curve is shifted forwards relative to another. $\phi = \frac{shift}{T} \times 360°$.

4.1.3 Conditions for simple harmonic motion

- $a \propto -x$
- period and amplitude are constant
- period is independent of amplitude
- displacement, velocity, and acceleration are sine or cosine functions of time

4.2 Travelling waves

4.2.1 Travelling waves

Wave: disturbance that travels in a medium (or a vacuum for electromagnetic waves) transferring energy and momentum from one place to another. The direction of propagation of the wave is the direction of energy transfer. There is no large-scale motion of the medium itself as the wave passes through.

4.2.2 Wavelength, frequency, period, and wave speed

- (λ) Wavelength: length of a complete oscillation.
- (f) Frequency: number of oscillations per second.
- (T) Period: time for one oscillation.
- (v) Wave speed: $v = \frac{\lambda}{T}$. The wave speed depends only on the properties of the medium and not on how it is produced.

4.2.3 Transverse and longitudinal waves

We call a wave transverse if the displacement is at right angles to the direction of energy transfer.

In a longitudinal wave the displacement is parallel to the direction of energy transfer.

A displacement-distance graph gives us the amplitude and wavelength of a wave.

A displacement-time graph gives us the amplitude and period of a wave.

A compression is a region of higher density; a rarefaction is a region of lower density.

4.2.4 The nature of electromagnetic waves

All EM waves move at the speed of light in a vacuum.

4.2.5 The nature of sound waves

They are longitudinal.

4.3 Wave characteristics

4.3.1 Wavefronts and rays

A wavefront is a surface through the crests and normal to the direction of energy transfer of the wave. Lines in the direction of energy transfer of the wave (and hence normal to the wavefronts) are called rays.

4.3.2 Amplitude and intensity

Intensity is the power incident on an area i.e $I = \frac{P}{a}$ Wm^{-2}.

For point sources of power the intensity at a distance x becomes: $I = \frac{P}{4\pi x^2}$.

We can see that $I \propto x^{-2}$, and so $I \propto A^2$.

4.3.3 Superposition

When two or more waves of the same type arrive at a given point in space at the same time, the displacement of the medium at that point is the algebraic sum of the individual displacements. So if y_1 and y_2 are individual displacements, then at the point where the two meet the total displacement has the value $y = y_1 + y_2$.

For pulses: fixed-end gives inverted pulse, free-end gives no change.

4.3.4 Polarization

An EM wave is said to be plane polarised if the electric field oscillates on the same plane.

Unpolarsied light can be polarised by passing it through a polariser.

Malus's law: $E = E_0 \cos\theta$, or $I = I_0 \cos^2\theta$.

Unpolarised light can also be partially polarised when it reflects off a non-metallic surface.

4.4 Wave behaviour

4.4.1 Reflection and refraction

The angle of incidence i (angle between the ray and the normal to the reflecting surface at the point of incidence) is equal to the angle of reflection r (angle between the normal and the reflected ray). The reflected and incident rays and the normal to the surface lie on the same plane, called the plane of incidence.

Refraction is the travel of light from one medium into another where it has a different speed.

4.4.2 Snell's law, critical angle and total internal reflection

Refraction changes the direction of the incident ray. Snell's law says: $\frac{\sin\theta_2}{\sin\theta_1} = \frac{c_1}{c_2}$.

In the case of light, we define the refractive index of a given medium n_m as: $n_m = \frac{c}{c_m}$.

For light, Snell's law can be rewritten: $\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1} = \frac{c_2}{c_1}$.

The angle of incidence for which the angle of refraction is 90° is called the critical angle.

There is no refracted ray when the angle of incidence is greater than the critical angle; there is just the reflected ray. This is known as total internal reflection.

4.4.3 Diffraction through a single-slit around objects

Diffraction takes place when a wave with wavelength comparable to or larger than the size of an aperture or an obstacle moves through or past the aperture or obstacle. In general, the larger the wavelength, the greater the effect.

Example: Sound can diffract around doors because its wavelength is roughly the same as the door size. Light cannot, since its wavelength is much smaller.

4.4.4 Interference patterns

Rays leaving different parts of the slit interfere and create complicated intensity patterns, with a central maximum and then subsidiary maxima/minima on either sides.

4.4.5 Double-slit interference

The resulting pattern (due to the principle of superposition) when two or more waves meet is known as interference.

Constructive interference is when individual waves add up and the amplitude is greater than for the individual waves (double if the waves are identical). It occurs when the path difference is $n\lambda$, with $n = 0, 1, 2, ...$ Waves are in phase.

Destructive interference is when indivdual waves cancel each other and the amplitude is less than for the individual waves (0 if the waves are identical). It occurs when the path difference is $(n + \frac{1}{2})\lambda$, with $n = 0, 1, 2, ...$ Waves are exactly out of phase.

Double-slit interference results in a pattern of bright and dark spots on a screen.

The distance between two consecutive bright/dark spots is called 'fringe spacing', denoted s, given by: $s = \frac{\lambda D}{d}$ where D is the distance between slits and the screen, and d is the distance between the slits.

4.4.6 Path difference

Path difference is the difference in distance of a point from two sources. For a point P some distance away from two wave sources, S_1 and S_2, the path difference will be $\delta r = |S_1P - S_2P|$.

4.5 Standing waves

4.5.1 The nature of standing waves

When two waves of the same speed, wavelength, and amplitude travelling in the opposite direction meet and interfere. The crests and troughs of a standing wave stay in the same place.

Some observations about standing waves:

- The wave does not 'move' left or right, as travelling waves do.
- Points between consecutive nodes are in phase and have the same velocity. Points between the next pair of consecutive nodes have the opposite velocity.
- The amplitude of oscillation is different at difference points on the string.
- A standing wave does not transfer energy.

4.5.2 Boundary Conditions

The ends of a standing wave are either nodes or antinodes, which determine the possible shape of the wave. These are known as boundary conditions. For example, a string with both ends fixed has the conditions node-node, since both ends are two nodes.

4.5.3 Nodes and antinodes

At some points of a standing wave, the displacement is always 0. These are called nodes. The distance between two consecutive nodes is half a wavelength.

At some points, the displacement is as large as possible. These are called antinodes.

A wave with node-node end conditions will have two nodes and one antinode. A wave with this condition will have the longest wavelength (and lowest frequency). It is called the first harmonic. The frequency of the first harmonic is called the fundamental frequency.

All harmonics have frequencies that are integral multiples of the fundamental frequency, i.e. of the first harmonic.

The wavelength for a standing wave with end conditions node-node or antinode-antinode is given by $\lambda_n = \frac{2L}{n}$, $n = 1, 2, 3, 4, ...$

The wavelength for a standing wave with end conditions node-antinode or antinode-node is given by $\lambda_n = \frac{4L}{n}$, $n = 1, 3, 5, 7, ...$

5 Electricity and Magnetism

5.1 Electric Fields

5.1.1 Charge

Charge is a property of matter. It can be negative (electrons) or positive (protons).

Like charges repel and unlike charges attract. This force of attraction and repulsion becomes weaker as the distance between the two bodies increases.

The SI Unit for charge is the Coulomb, symbol C.

Charge is quantised. The magnitude of the charge on the proton is equal to 1.6×10^{-19} C. This amount is symbolised by e. The charge of an electron is $-e$.

Charge is conserved. It cannot be created or destroyed. The total charge in a system cannot change.

Free electrons are those that do not belong to a particular atom and are able to move about and carry charge through the metal. Materials with many free electrons are called conductors. Those that do not are called insulators.

5.1.2 Electric Field

The space around a charge contains an electric field. This can be tested by bringing a small test charge into the space and observing whether it experiences a force or not.

Electric field strength is defined as the electric force per unit charge experienced by a small, positive point charge:

$$E = \frac{F}{q}$$

Electric field is a vector quantity. The direction is the same as the force experienced by the charge. The unit of electric field is N C^{-1}.

Using Coulomb's law (below) we can also find:

$$E = k\frac{Q}{r^2}$$

5.1.3 Coulomb's Law

The force between two charges is inversely proportional to the square of the separation of the charges and proportional to the product of the two charges:

$$F = k\frac{q_1 q_2}{r^2}$$

The constant k is also written $\frac{1}{4\pi\epsilon_0}$, so that:

$$F = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{r^2}$$

The factor $\frac{1}{4\pi\epsilon_0}$ is 8.99×10^9 N m^2 C^{-2} in a vacuum. The constant ϵ_0 is the electric permittivity of vacuum and $\epsilon_0 = 8.85 \times 10^{-12}$ C^2 N^{-1} m^{-2}. This constant is different for different media.

5.1.4 Electric Current

The electric field inside a conductor is zero in static situations (when there is no current). If an electric field is applied across it, the free electrons experience a force which pushes them in the opposite direction to the field.

Electric current is defined as the rate of flow of charge through a conductor:

$$I = \frac{\Delta q}{\Delta t}$$

The unit of electric current is the ampere (symbol A), equal to flow of one coulomb per second (1 A = 1 C s^{-1}).

For a conducting wire, the change in charge is given by $nAvq\Delta t$, where n is the number of electrons per unit volume, A is the cross-sectional area of the wire, v is the drift speed, q is the charge and Δt is the change in time.

Thus, for conducting wires:

$$I = nAvq$$

Electric current can be measured using an ammeter, connected to the device in series. An ideal ammeter has zero resistance.

5.1.5 Direct Current

When electrons move in the same direction, it is known as direct current.

5.1.6 Potential Difference

The potential difference V between two points is the work done per unit charge to move a point charge from one point to another:

$$V = \frac{W}{q}$$

The unit of potential is the volt, V, and 1 V = 1 J C^{-1}.

Whenever there is a potential difference, there has to be an electric field.

The electronvolt is another unit for dealing with smaller charges:

$$1\text{eV} = 1.6 \times 10^{-19}\text{J}$$

It is the work done in moving one electron charge across a potential difference of one volt.

Potential difference can be measured using a voltmeter, connected in parallel to the device. An ideal voltmeter has infinite resistance, so that no current passes through it.

5.2 Heating effects of electric currents

5.2.1 Circuit diagrams

Refer to data booklet for symbols.

For resistors connected in series, the total resistance is:

$$R_{total} = R_1 + R_2 + ... + R_n$$

For resistors connected in parallel, the total resistance is:

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + ... + \frac{1}{R_n}$$

5.2.2 Kirchhoff's circuit laws

Kirchhoff's current law:

$$\sum I_{in} = \sum I_{out}$$

In words, the total current entering a junction is equal to the total current exiting a junction.

Kirchhoff's loop law:

$$\sum V = 0$$

In words, the sum of voltages across each resistor is always equal to 0. This is a consequence of the conservation of energy.

5.2.3 Heating effect of current and its consequences

An electric field within a conductor accelerates the free electrons. Electrons gain kinetic energy and suffer inelastic collisions with the metal atoms. Energy is transferred to the atoms and this results in an increase in the temperature of the wire.

5.2.4 Resistance expressed as $R = \frac{V}{I}$

Electric resistance is a property of conductors which determines how much current will flow for a given potential difference:

$$R = \frac{V}{I}$$

The unit is volt per ampere, also called the ohm, with symbol Ω.

5.2.5 Ohm's law

When the temperature of most metallic conductors is kept constant, the current through the conductor is proportional to the potential difference across it:

$$I \propto V$$

This is known as Ohm's law.

5.2.6 Resistivity

From experimentation, the electric resistance of a wire at a fixed temperature has been found to be proportional to its length and inversely proportional to its cross-sectional area:

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

The constant ρ is called resistivity, and depends on the conductor and the temperature. The unit of resistivity is Ωm.

5.2.7 Power dissipation

The potential difference at the ends of a resistor is commonly called ‘voltage’, and is given by $V = IR$.

Power is the rate of work done, and so the power dissipated in a resistor is given by:

$$P = IV = RI^2 = \frac{V^2}{R}$$

5.3 Electric Cells

5.3.1 Cells

Cells or batteries are sources of potential difference that can be connected in a circuit. They convert various forms of energy into electrical energy.

One characteristic of a cell is the amount of charge it can deliver in its lifetime, known as its capacity. The bigger the current, the faster the cell discharges. After an initial sudden drop, the terminal voltage remains almost constant until the capacity is exhausted and there is again a sudden drop.

5.3.2 Internal Resistance

A real battery has internal resistance, denoted by r, connected to it in series. It cannot be isolated from the battery. An ideal battery is one with no internal resistance.

5.3.3 Secondary Cells

A primary cell is one which can only be used once, until it runs out. A secondary cell is one which is rechargeable and can be used again.

5.3.4 Terminal potential difference

The current that leaves a real battery is I. The potential difference across the internal resistance is Ir. Without the internal resistance, the potential difference across the battery is its emf, ϵ. Thus, the voltage across the terminals of a real battery (including its internal resistance) is:

$$V = \epsilon - Ir$$

5.3.5 Electromotive force (emf)

Definition. The emf ϵ of a battery is the work done per unit charge in moving charge from one terminal of the battery to the other.

$$\epsilon = \frac{W}{q}$$

It is also equal to power per unit current, i.e. $\epsilon = \frac{P}{I}$. The unit of emf is the volt, V.

5.4 Magnetic effects of electric currents

5.4.1 Magnetic fields

A region of influence created by a magnet, similar to (but distinct from) an electric field. A magnetic field can also be produced by an electric current.

The magnetic field, B, is a vector quantity.

We draw imaginary curves, called magnetic field lines, around a magnet to depict the magnetic field. Magnetic field lines always exit from the north pole, and enter at the south pole.

The direction of a magnetic field around a straight wire carrying a current can be determined using the right-hand grip rule.

5.4.2 Magnetic forces

An electric charge moving through a region of magnetic field experiences a type of force called a magnetic force.

There is no magnetic force on a moving charge if the charge moves along the field direction (i.e. the velocity of the charge is parallel to the direction of the field). In any other direction, there will be a force on the charge.

Definition. If the magnetic force is F on a charge q moving with speed v, at an angle θ to the direction of the field, then the magnitude of the field, called magnetic flux density, is defined as:

$$B = \frac{F}{qv\sin\theta}$$

The unit of magnetic flux density is the tesla (T).

Thus, a charge q moving with speed v inside a magnetic field of magnetic flux density B will experience a magnetic force F given by:

$$F = qvB\sin\theta$$

The right-hand rule can be used to determine the direction of the magnetic field.

The magnetic force on a wire of length L is given by:

$$F = BIL\sin\theta$$

Charges moving at right angles to a magnetic field follow the path of a circle. No work is done by the magnetic force, since it is at a right angle to the velocity of the charge (recall, $W = Fd\cos\theta$).

6 Circular Motion and Gravitation

6.1 Circular Motion

6.1.1 Period, frequency, angular displacement and angular velocity

Definition. Period is the time taken to complete one full revolution, denoted by T. Since an object covers a distance of $2\pi r$ in time T seconds, we have:

$$v = \frac{2\pi r}{T}$$

where r is the radius of the circular path and v is the linear speed.

Definition. The angular speed of an object, denoted ω, is the angle swept per time taken:

$$\omega = \frac{\Delta\theta}{\Delta t}$$

Its unit is radians per second, rads^{-1}.

For one complete revolution, $\Delta\theta = 2\pi$ and $\Delta t = T$, so:

$$\omega = \frac{2\pi}{T}$$

Using the definition of frequency, $f = \frac{1}{T}$, we also have that $\omega = 2\pi f$.

Using these equations we can also find the relationship between linear speed and angular speed:

$$v = r\omega$$

6.1.2 Centripetal force

A body moving in a circle is always accelerating (since the direction of its velocity is changing). Thus, there must also be a net force acting on it. For constant speed, the direction of both the acceleration and force is towards the centre of the circle. The magnitude of the force is given by:

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

This is also equivalent to $F = m\omega^2 r$.

Note: centripetal force is not a new force. It is only a component of the forces already acting on an object!

The work done by a centripetal force is 0, since the force is at right angles to the direction of motion (recall that $W = Fd\cos\theta$).

6.1.3 Centripetal acceleration

Definition. A body moving along a circle of radius r with speed v experiences centripetal acceleration that has magnitude given by:

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

and is directed towards the centre of the circle.

Some equivalent expressions for centripetal acceleration:

$$a = \omega^2 r$$
$$a = \frac{4\pi^2 r}{T^2}$$
$$a = 4\pi^2 r f^2$$

6.2 Newton's law of gravitation

6.2.1 Newton's law of gravitation

Definition. The attractive force of gravitation between two point masses is given by:

$$F = G\frac{M_1 M_2}{r^2}$$

where M_1 and M_2 are the masses of the attracting bodies, r the distance between their centres of mass and G a constant called Newton's constant of universal gravitation. It has the value $G = 6.667 \times 10^{-11}$ Nm^{2}kg^{-2}. The direction of the force is along the line joining the two masses.

Equating the formula for centripetal force and the force of gravitation gives:

$$v = \sqrt{\frac{GM}{r}}$$

This is the speed of a particle mass orbiting a larger body of mass M in a circular orbit of radius r (assuming the only force on the particle is the force of gravitation).

6.2.2 Gravitational field strength

A mass M is said to create a gravitational field in the space around it.

Definition. The gravitational field strength at a certain point is the gravitational force per unit mass experienced by a small point mass m placed at that point:

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

The unit of gravitational field strength is Nkg^{-1}.

We also have the gravitational field strength of a spherical mass M given by:

$$g = G\frac{M}{r^2}$$

Gravitational field strength is also a vector quantity, whose direction is towards the centre of the mass creating the field.

7 Atomic, Nuclear and Particle physics

7.1 Discrete energy and radioactivity

7.1.1 Discrete energy and discrete energy levels

7.1.2 Transitions between energy levels

7.1.3 Radioactive decay

7.1.4 Fundamental forces and their properties

7.1.5 Alpha particles, beta particles and gamma rays

7.1.6 Half-life

7.1.7 Absorption characteristics of decay particles

7.1.8 Isotopes

7.1.9 Background radiation

7.2 Nuclear reactions

7.2.1 The unified atomic mass unit

7.2.2 Mass defect and nuclear binding energy

7.2.3 Nuclear fission and nuclear fusion

7.3 The structure of matter

7.3.1 Quarks, leptons and their antiparticles

7.3.2 Hadrons, baryons and mesons

7.3.3 The conservation laws of charge, baryon number, lepton number and strangeness

7.3.4 The nature and range of the strong nuclear force, weak nuclear force and electromagnetic force

7.3.5 Exchange particles

7.3.6 Feynman diagrams

7.3.7 Confinement

7.3.8 The Higgs boson

8 Energy Production

8.1 Energy sources

8.1.1 Specific energy and energy density of fuel sources

8.1.2 Sankey diagrams

8.1.3 Primary energy sources

8.1.4 Electricity as a secondary and versatile form of energy

8.1.5 Renewable and non-renewable energy sources

8.2 Thermal energy transfer

8.2.1 Conduction, convection and thermal radiation

8.2.2 Black-body radiation

8.2.3 Albedo and emissivity

8.2.4 The solar constant

8.2.5 The greenhouse effect

8.2.6 Energy balance in the Earth surface-atmosphere system

9 Topic 9

10 Topic 10

11 Topic 11

12 Topic 12