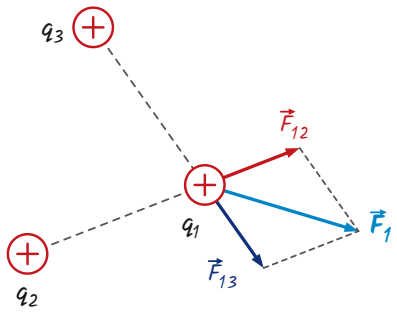
Superposition Principle for Multiple Charges

The total force on a charge due to a number of other charges is the **vector sum** of the individual forces, each calculated as if the other charges were absent.

$$\vec{F}_1 = \vec{F}_{12} + \vec{F}_{13} + \vec{F}_{14} + \ldots + \vec{F}_{1n}$$

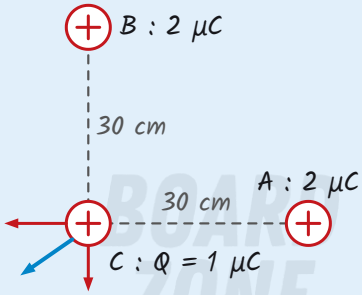


For two forces at angle θ, the magnitude of the resultant is :

$$F = \sqrt{F_1^2 + F_2^2 + 2F_1F_2\cos\theta}$$

SOLVED NUMERICAL 5

Charges of 2 μC each are at A and B, and Q = 1 μC is at C, with angle ACB = 90° and CA = CB = 30 cm. Find the net force on Q.



GIVEN DATA $q_A = q_B = 2 \times 10^{-6}$ C , $Q = 1 \times 10^{-6}$ C , $r = 0.30$ m , $\theta = 90°$

REQUIRED QUANTITY Net force on Q

RELEVANT FORMULA Each force $F = k\,|q\,Q| / r^2$

For perpendicular forces $F_{net} = \sqrt{F_1^2 + F_2^2}$

SUBSTITUTION

$$F_1 = F_2 = \frac{9 \times 10^9 \times 2 \times 10^{-6} \times 1 \times 10^{-6}}{(0.30)^2}$$

STEP-BY-STEP CALCULATION

$$F_1 = F_2 = 0.2\ N$$

$$F_{net} = \sqrt{(0.2)^2 + (0.2)^2}$$

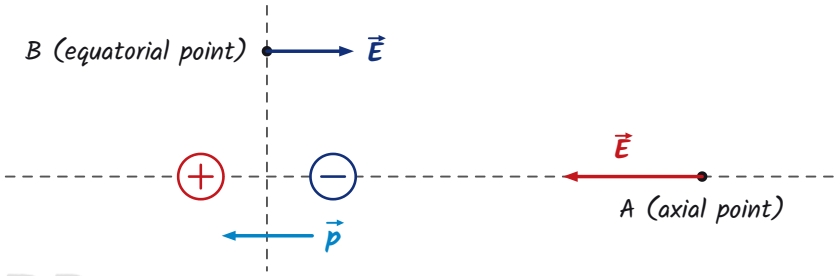
$$F_{net} = 0.2\sqrt{2} = 0.28\ N$$

FINAL ANSWER $F_{net} = 0.28$ N at 45° to each force, directed away from A and B

Electric Field

A charge changes the space around it. Any other charge placed there feels a force. This region of influence is the **electric field**.

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Point (ideal) dipole : if $q \to \infty$ and $a \to 0$ while $p = q \times 2a$ stays finite, the short-dipole results become exact for every r. So these formulas are the field of a point dipole.

Remember This

The field of a dipole falls as $1/r^3$, faster than the $1/r^2$ of a point charge, because the fields of $+q$ and $-q$ nearly cancel far away.

SOLVED NUMERICAL 8

A short dipole has charges $\pm 5\ \mu C$ separated by 4 mm. Find its dipole moment, and the field at 20 cm from its centre on (i) the axial line (ii) the equatorial line.

GIVEN DATA $q = 5 \times 10^{-6}\ C$, $2a = 4 \times 10^{-3}\ m$, $r = 0.20\ m$

REQUIRED QUANTITY p, E_{ax} and E_{eq}

RELEVANT FORMULA $p = q \times 2a$, $E_{ax} = 2kp/r^3$, $E_{eq} = kp/r^3$ (short dipole, as $a \ll r$)

SUBSTITUTION

$$p = 5 \times 10^{-6} \times 4 \times 10^{-3}$$

$$E_{ax} = \frac{2 \times 9 \times 10^9 \times 2 \times 10^{-8}}{(0.20)^3}$$

STEP-BY-STEP CALCULATION

$$p = 2 \times 10^{-8}\ C\ m$$

$$E_{ax} = \frac{360}{8 \times 10^{-3}}$$

$$E_{ax} = 4.5 \times 10^4\ N/C$$

$$E_{eq} = \frac{E_{ax}}{2}$$

FINAL ANSWER

$p = 2 \times 10^{-8}\ C\ m$ directed from $-q$ to $+q$

$E_{ax} = 4.5 \times 10^4\ N/C$ along $\vec{p}$

$E_{eq} = 2.25 \times 10^4\ N/C$ opposite to $\vec{p}$

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SOLVED NUMERICAL 10

A uniform field $\vec{E}$ of magnitude 3×10^3 N/C passes through a square of side 10 cm. Find the flux when the normal to the square makes (i) 0° (ii) 60° with the field.

GIVEN DATA $E = 3 \times 10^3$ N/C , side = 0.10 m , $S = (0.10)^2 = 0.01$ m²

REQUIRED QUANTITY ϕ_E for $\theta = 0°$ and $\theta = 60°$

RELEVANT FORMULA $\phi_E = E\,S\cos\theta$

SUBSTITUTION

$$\phi_1 = 3 \times 10^3 \times 0.01 \times \cos 0°$$
$$\phi_2 = 3 \times 10^3 \times 0.01 \times \cos 60°$$

STEP-BY-STEP CALCULATION

$$\phi_1 = 30 \times 1$$
$$\phi_2 = 30 \times 0.5$$

FINAL ANSWER

$$\phi_1 = 30 \text{ N m}^2 \text{ C}^{-1}$$
$$\phi_2 = 15 \text{ N m}^2 \text{ C}^{-1}$$

Gauss's Theorem (Gauss's Law)

Gauss's theorem states that the total flux through a closed surface is $1/\varepsilon_0$ times the net charge enclosed by the closed surface.

$$\phi_E = \oint \vec{E} \cdot d\vec{S} = \frac{q}{\varepsilon_0}$$

q = net charge enclosed by the closed surface

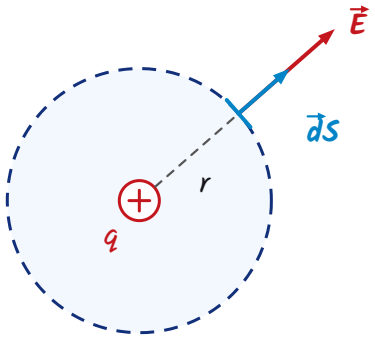
Proof :- Let us take a point charge q at the centre of a sphere of radius r.

At every point of the sphere, $\vec{E}$ and $d\vec{S}$ are both radial, so $\theta = 0°$.

$$d\phi_E = E\,dS\cos\theta$$
$$d\phi_E = E\,dS\cos 0°$$
$$d\phi_E = E\,dS$$

$$\phi_E = \oint E\,dS$$ integrate over the sphere

$$\phi_E = \oint \frac{kq}{r^2}\,dS$$ $E = kq/r^2$

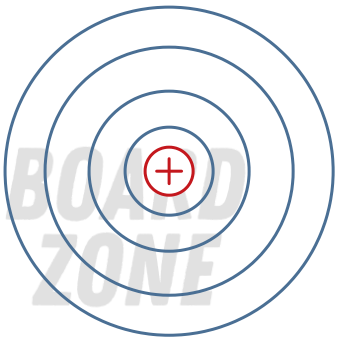


Gaussian sphere

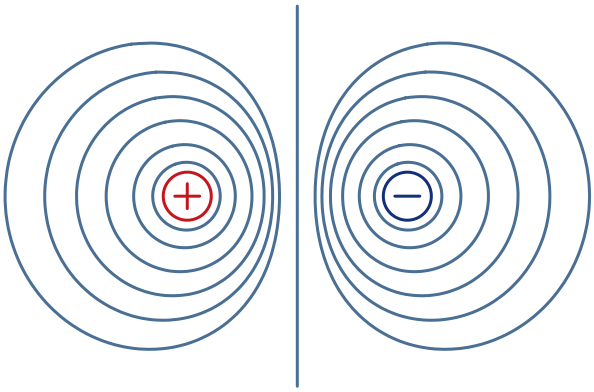
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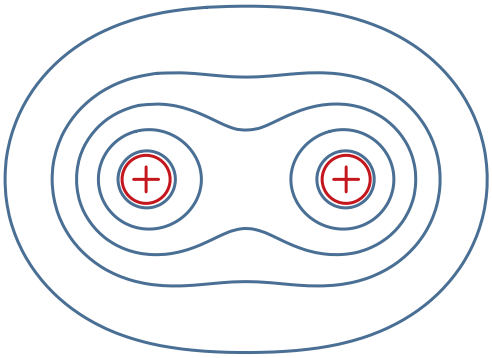
Equipotential Surfaces for Different Charge Systems



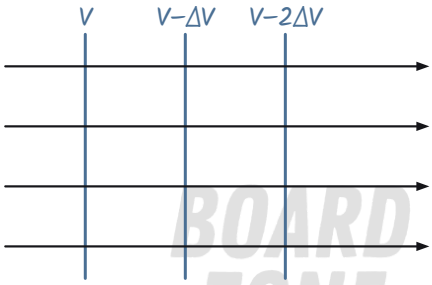
Positive point charge



Two equal and opposite charges



Two equal positive charges



Uniform electric field

Electric Potential Energy

Potential energy :- It is the energy stored in a body when work is done against a conservative force, such as the electrostatic, gravitational or elastic force.

Electric potential energy :- The energy stored in a system of charges when work is done against the electrostatic force in bringing the charges to their positions is called electric potential energy.

Potential Energy of a System of Two Point Charges

Let a charge q_1 be fixed at A, and let q_2 be brought from infinity to a point B at distance r from it.

$$F = \frac{kq_1q_2}{x^2}$$ force to be overcome at distance x

$$dW = F\,dl\cos0° = \frac{kq_1q_2}{x^2}(-dx)$$ $dl = -dx$

derivation continues on the next page

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SOLVED NUMERICAL 6

Three charges of +1 μC each are placed at the corners of an equilateral triangle of side 10 cm. Find the potential energy of the system.

GIVEN DATA $q = 10^{-6}$ C for each , $a = 0.10$ m

REQUIRED QUANTITY Potential energy U

RELEVANT FORMULA $U = k\,(q_1q_2 + q_2q_3 + q_3q_1) / a$

SUBSTITUTION

$$U = 3 \times \frac{9 \times 10^{9} \times (10^{-6})^2}{0.10}$$

STEP-BY-STEP CALCULATION

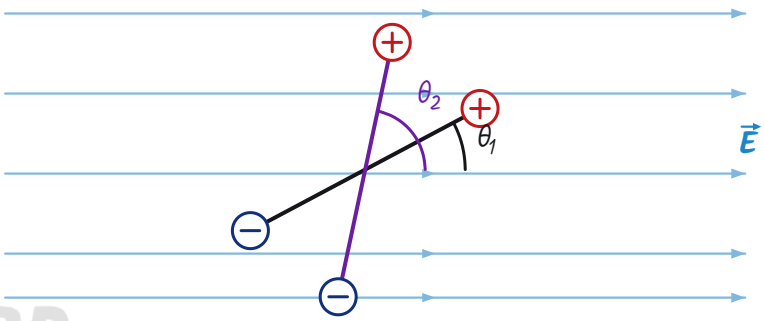
$$U = 3 \times \frac{9 \times 10^{-3}}{0.10}$$

$$U = 3 \times 0.09$$

FINAL ANSWER $U = 0.27$ J positive, as all the charges are alike

Work Done in Rotating a Dipole in a Uniform Electric Field

A dipole of moment p is in a uniform field E, making angle θ_1 with it. We rotate it to angle θ_2 against the torque $\tau = pE\sin\theta$.



$dW = \tau\, d\theta = pE \sin\theta\, d\theta$ — work for a small rotation $d\theta$

$W = pE \int \sin\theta\, d\theta$ — integrate from θ_1 to θ_2

$W = pE \left[-\cos\theta\right]$ — put the limits

$W = -pE\,(\cos\theta_2 - \cos\theta_1)$

$$W = U = pE\,(\cos\theta_1 - \cos\theta_2)$$

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Important Concept

Comparing $R = \rho\, l/A$ with the result above, **resistivity $\rho = m / (n e^2 \tau)$** depends only on the **material (n, τ) and temperature** ; it does not depend on the size. On heating, τ decreases (more collisions), so ρ increases for metals.

SOLVED NUMERICAL 5

A copper wire of cross-section 2 mm^2 carries a current of 3 A. Find the drift velocity of the free electrons. ($n = 8.5 \times 10^{28}\ m^{-3}$, $e = 1.6 \times 10^{-19}\ C$)

GIVEN DATA $A = 2 \times 10^{-6}\ m^2$, $I = 3\ A$, $n = 8.5 \times 10^{28}\ m^{-3}$

REQUIRED QUANTITY Drift velocity v_d

RELEVANT FORMULA $I = n\, e\, A\, v_d \Rightarrow v_d = \dfrac{I}{n\, e\, A}$

SUBSTITUTION

$$v_d = \frac{3}{8.5 \times 10^{28} \times 1.6 \times 10^{-19} \times 2 \times 10^{-6}}$$

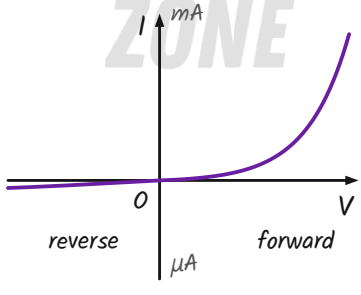
STEP-BY-STEP CALCULATION

$$v_d = \frac{3}{2.72 \times 10^{4}}$$

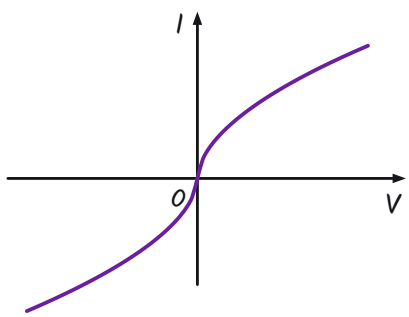
FINAL ANSWER $v_d \approx 1.1 \times 10^{-4}\ m/s$ ≈ 0.11 mm/s

Ohmic and Non-Ohmic Substances

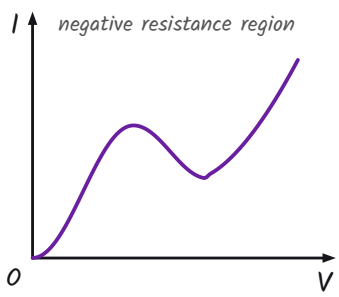
- **Ohmic substances** obey Ohm's law ; their V–I graph is a **straight line** through the origin. Example : all metallic conductors.
- **Non-ohmic substances** do not obey Ohm's law ; the V–I graph is **not a straight line**. Examples : **p–n junction diode**, solar cell, bulb filament, thermistor.



(a) p–n junction diode



(b) bulb filament

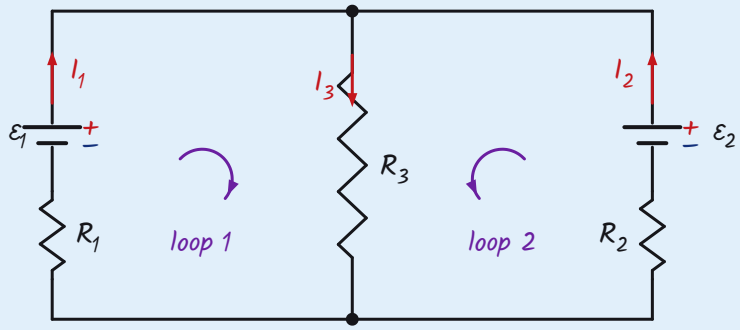


(c) GaAs

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SOLVED NUMERICAL 6

In the circuit shown, $\varepsilon_1 = 10$ V, $\varepsilon_2 = 5$ V, $R_1 = 2\ \Omega$, $R_2 = 1\ \Omega$ and $R_3 = 4\ \Omega$ (the cells have negligible internal resistance). Find the currents I_1, I_2 and I_3.



GIVEN DATA $\varepsilon_1 = 10$ V , $\varepsilon_2 = 5$ V , $R_1 = 2\ \Omega$, $R_2 = 1\ \Omega$, $R_3 = 4\ \Omega$

REQUIRED QUANTITY Currents I_1 , I_2 , I_3 in the three branches

RELEVANT FORMULA Junction law : $I_3 = I_1 + I_2$; Loop law : $\Sigma\ \varepsilon = \Sigma\ IR$

SUBSTITUTION

Loop 1 (left loop) :

$$10 - 2\,I_1 - 4\,I_3 = 0$$

Loop 2 (right loop) :

$$5 - 1\cdot I_2 - 4\,I_3 = 0$$

STEP-BY-STEP CALCULATION

Put $I_3 = I_1 + I_2$ in both loop equations :

$$6\,I_1 + 4\,I_2 = 10$$

$$4\,I_1 + 5\,I_2 = 5$$

Solving the two equations :

$$I_2 = -\frac{5}{7}\ A\ ,\ I_1 = \frac{15}{7}\ A\ ,\ I_3 = \frac{10}{7}\ A$$

FINAL ANSWER

$I_1 = 15/7 \approx 2.14$ A

$I_2 = -5/7 \approx -0.71$ A the negative sign means ε_2 is being charged

$I_3 = 10/7 \approx 1.43$ A

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SOLVED NUMERICAL 7

In a balanced Wheatstone bridge P = 6 Ω, Q = 9 Ω and S = 12 Ω. Find the resistance R.

GIVEN DATA $P = 6\ \Omega$, $Q = 9\ \Omega$, $S = 12\ \Omega$

REQUIRED QUANTITY Resistance R

RELEVANT FORMULA $\frac{P}{Q} = \frac{R}{S}$

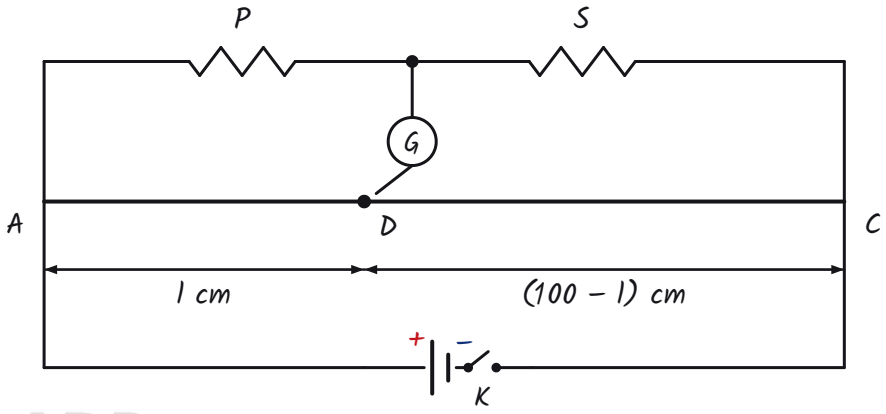
SUBSTITUTION $R = \frac{P\,S}{Q} = \frac{6 \times 12}{9}$

STEP-BY-STEP CALCULATION $R = \frac{72}{9}$

FINAL ANSWER $R = 8\ \Omega$

Meter Bridge

The meter bridge is a practical form of the Wheatstone bridge. A **uniform wire AC of length 100 cm** forms two arms. A known resistance P (resistance box) is in the left gap and the unknown resistance S in the right gap. A **jockey** J is slid on the wire until the galvanometer shows **no deflection**. Let AJ = l cm, so JC = (100 − l) cm.



$$\frac{P}{S} = \frac{R_{AJ}}{R_{JC}}$$ balance condition of the bridge

$$\frac{P}{S} = \frac{\rho\, l / A}{\rho\,(100 - l) / A}$$ $R = \rho\, l / A$ for the uniform wire

$$\frac{P}{S} = \frac{l}{100 - l}$$ ρ and A cancel

$$S = P\,\frac{(100 - l)}{l}$$

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$\oint \vec{B} \cdot d\vec{l} = \mu_0 I$ Ampere's law

$\oint B\, dl \cos 0° = \mu_0 I$ B ∥ dl on the loop

$B \oint dl = \mu_0 I$

$B\,(2\pi r) = \mu_0 I$ $\oint dl = 2\pi r$

BOARD ZONE

$$B = \frac{\mu_0 I}{2\pi r}$$

$B \propto 1/r$

SOLVED NUMERICAL 3

A long straight wire carries a current of 10 A. Find the magnetic field at a distance of 5 cm from it. ($\mu_0 = 4\pi \times 10^{-7}$ T m A^{-1})

GIVEN DATA $I = 10$ A , $r = 5$ cm $= 0.05$ m

REQUIRED QUANTITY Magnetic field B

RELEVANT FORMULA $B = \frac{\mu_0 I}{2\pi r}$

BOARD ZONE

SUBSTITUTION $B = \frac{4\pi \times 10^{-7} \times 10}{2\pi \times 0.05}$

STEP-BY-STEP CALCULATION $B = \frac{2 \times 10^{-7} \times 10}{0.05}$

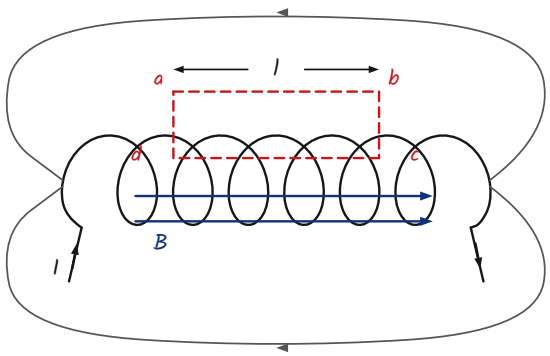
$B = 4 \times 10^{-5}$ T

FINAL ANSWER $B = 4 \times 10^{-5}$ T circles around the wire (right-hand thumb rule)

(2) B for a solenoid

A solenoid is a long wire wound closely in the form of a helix. The magnetic field of a long solenoid is **uniform inside** it and negligible outside. Such a field is used to magnetise other substances.

BOARD ZONE



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SOLVED NUMERICAL 8

Two long parallel wires 2 cm apart carry currents of 10 A and 5 A in the same direction. Find the force per unit length between them. Is it attractive or repulsive?

GIVEN DATA $I_1 = 10\ A$, $I_2 = 5\ A$, $d = 2\ cm = 0.02\ m$

REQUIRED QUANTITY Force per unit length F/l

RELEVANT FORMULA $\frac{F}{l} = \frac{\mu_0}{2\pi}\frac{I_1 I_2}{d}$

SUBSTITUTION $\frac{F}{l} = \frac{2 \times 10^{-7} \times 10 \times 5}{0.02}$

STEP-BY-STEP CALCULATION $\frac{F}{l} = \frac{10^{-5}}{0.02}$

FINAL ANSWER $F/l = 5 \times 10^{-4}\ N/m$ attractive (currents in the same direction)

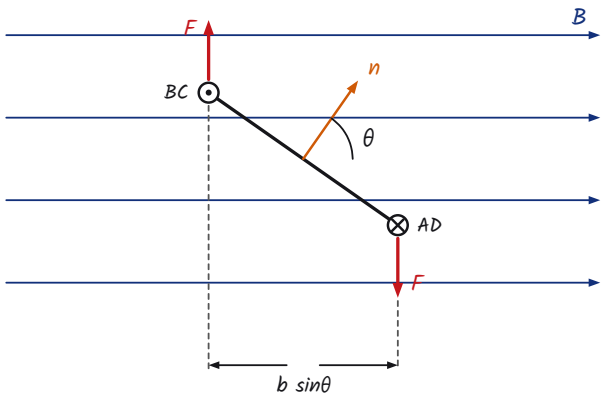
Exam Point of View

Q. Why does a solenoid contract in length when a current is passed through it?

Ans. Every turn of the solenoid carries current in the **same direction**. Parallel currents in the same direction **attract** each other, so adjacent turns attract each other and the solenoid contracts along its length.

Torque on a Current-Carrying Loop in a Uniform Magnetic Field

Let us take a rectangular loop of dimensions a × b carrying current I in a strong uniform magnetic field $\vec{B}$. Let the angle between the **normal to the loop** (area vector) and $\vec{B}$ be θ. The forces on the four sides :



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Current Loop as a Magnetic Dipole

A current-carrying loop behaves like a bar magnet. Its magnetic moment is the product of the **current, the number of turns and the area** :

$$\vec{M} = N\, I\, \vec{A}$$

direction of M : along the normal to the loop (by the right-hand rule) ; unit A m^2

A **solenoid** carrying current behaves like a bar magnet : its one end acts as a north pole and the other as a south pole. The field outside it is similar to that of a bar magnet.

SOLVED NUMERICAL 5

A solenoid of 200 turns and cross-section 0.01 m^2 carries a current of 2 A. Find its magnetic moment.

GIVEN DATA	$N = 200$, $A = 0.01\ m^2$, $I = 2\ A$
REQUIRED QUANTITY	Magnetic moment M
RELEVANT FORMULA	$M = N\, I\, A$
SUBSTITUTION	$M = 200 \times 2 \times 0.01$
STEP-BY-STEP CALCULATION	$M = 4\ A\ m^2$
FINAL ANSWER	**$M = 4\ A\ m^2$** along the axis of the solenoid

Gauss's Law in Magnetism

Gauss's law for magnetism :- The net magnetic flux through any closed surface is always **zero**.

$$\oint \vec{B} \cdot d\vec{A} = 0$$

magnetic monopoles do not exist ; the number of field lines entering a closed surface equals the number leaving it

Exam Point of View

Q. Why can an isolated magnetic pole not exist?

Ans. Magnetic field lines always form closed loops, so as many lines enter a closed surface as leave it, and the net flux is zero. A single pole would need lines only leaving (or only entering), which would break Gauss's law of magnetism. When a magnet is cut, each piece again has two poles.

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SOLVED NUMERICAL 6

A material is placed in a magnetic intensity H = 2000 A/m. The magnetisation produced is 0.4 A/m. Find the susceptibility, the relative permeability and the magnetic field B inside the material.

GIVEN DATA $H = 2000\ A/m$, $I = 0.4\ A/m$

REQUIRED QUANTITY χ , μ_r and B

RELEVANT FORMULA $\chi = \frac{I}{H}$, $\mu_r = 1 + \chi$, $B = \mu_0 \mu_r H$

SUBSTITUTION

$$\chi = \frac{0.4}{2000}$$

$$B = 4\pi \times 10^{-7} \times 1.0002 \times 2000$$

STEP-BY-STEP CALCULATION

$$\chi = 2 \times 10^{-4}$$

$$\mu_r = 1 + 2 \times 10^{-4} = 1.0002$$

$$B = 2.514 \times 10^{-3}\ T$$

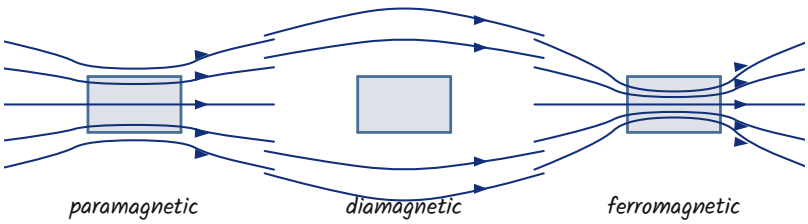
FINAL ANSWER

$\chi = 2 \times 10^{-4}$

$\mu r = 1.0002$

$B = 2.514 \times 10^{-3}\ T$

Classification of Magnetic Materials



Property	Diamagnetic	Paramagnetic	Ferromagnetic
Effect of the field	Weakly **repelled**	Weakly **attracted**	**Strongly attracted**
Susceptibility χ	Small and **negative**	Small and **positive**	**Very large** and positive
Relative permeability	$\mu r < 1$	$\mu r > 1$ (slightly)	$\mu r \gg 1$
Field lines	Repelled out of the material	Concentrated slightly inside	Strongly concentrated inside

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(3) For a small area element dS on any surface : $d\phi_B = \vec{B} \cdot d\vec{S} = B\, dS \cos\theta$, and the total flux is $\phi_B = \int \vec{B} \cdot d\vec{S}$.

S.I. unit : tesla metre² (T m^2) or **weber (Wb)**. 1 Wb = 1 T × 1 m^2 × cos 0°. Flux is a **scalar** quantity. Its dimensions are [M L^2 T^{-2} A^{-1}].

Angle θ between B and S	Flux	Meaning
θ = 0° (surface ⊥ field)	ϕ_B = BS (maximum)	all the lines pass through the surface
θ = 90° (surface ∥ field)	ϕ_B = 0	no line passes through the surface

SOLVED NUMERICAL 1

A coil of area 0.05 m^2 is placed in a uniform magnetic field of 0.4 T. The normal to the coil makes an angle of 60° with the field. Find the magnetic flux through the coil.

GIVEN DATA	S = 0.05 m^2 , B = 0.4 T , θ = 60°
REQUIRED QUANTITY	Magnetic flux ϕ_B
RELEVANT FORMULA	ϕ_B = BS cosθ
SUBSTITUTION	ϕ_B = 0.4 × 0.05 × cos60°
STEP-BY-STEP CALCULATION	ϕ_B = 0.02 × 0.5
FINAL ANSWER	ϕ_B = 0.01 Wb = 1 × 10^{-2} Wb

Faraday's Law of Electromagnetic Induction

First law : Whenever the magnetic flux linked with a circuit changes, an emf is induced in it.

Second law : The magnitude of the induced emf is directly proportional to the **rate of change of magnetic flux** through the circuit.

$$|\varepsilon| \propto \frac{\Delta\phi_B}{\Delta t}$$ Faraday's second law

$$|\varepsilon| \propto \frac{d\phi_B}{dt}$$ for a very small interval

$$|\varepsilon| = k\,\frac{d\phi_B}{dt}$$ k = constant

derivation continues on the next page

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SOLVED NUMERICAL 5

A coil of 200 turns and area 0.05 m^2 rotates at 100 rad/s in a uniform field of 0.4 T. Find the maximum emf, and the emf when the coil has turned 30° from the position of zero emf.

GIVEN DATA	$N = 200$, $A = 0.05\ m^2$, $B = 0.4\ T$, $\omega = 100\ rad/s$, $\theta = 30°$
REQUIRED QUANTITY	Peak emf ε_0 and emf at $\theta = 30°$
RELEVANT FORMULA	$\varepsilon_0 = NBA\omega$, $\varepsilon = \varepsilon_0 \sin\theta$
SUBSTITUTION	$\varepsilon_0 = 200 \times 0.4 \times 0.05 \times 100$
STEP-BY-STEP CALCULATION	$\varepsilon_0 = 400\ V$ $\varepsilon = 400 \times \sin 30° = 400 \times 0.5 = 200\ V$

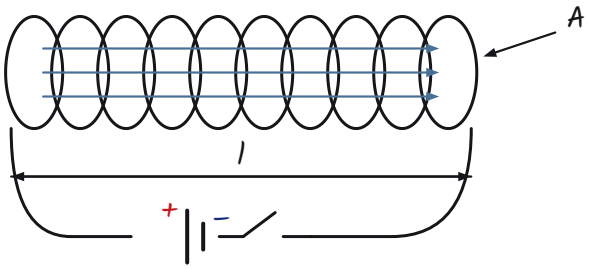
FINAL ANSWER

$\varepsilon_0 = 400\ V$ peak emf

$\varepsilon = 200\ V$ at $\theta = 30°$

Self Induction

Self induction :- It is the phenomenon of production of an induced emf in a coil when the **current passing through the same coil changes.**



When the current in a coil changes, the flux linked with the coil changes, and this induces an emf in the coil itself. The flux linked is proportional to the current :

$$\phi_B = LI \ , \ L = \frac{\phi_B}{I}$$

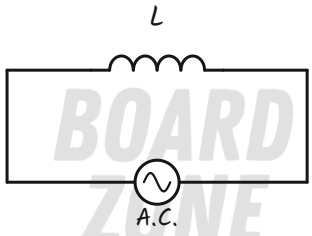
L = coefficient of self induction (self inductance) ; ϕ_B = total flux linked with the coil

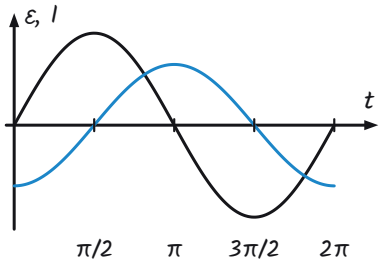
$$\varepsilon = -\frac{d\phi_B}{dt} = -\frac{d\,(LI)}{dt}$$ from $\phi = LI$

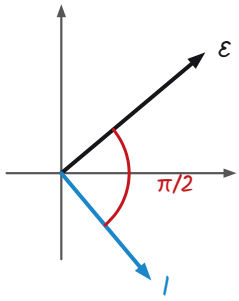
$$\varepsilon = -L\,\frac{dI}{dt}$$ L is constant

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A.C. Circuit Containing Only an Inductor







Current in a purely inductive circuit

$\varepsilon = \varepsilon_0 \sin \omega t$ (1)

$\varepsilon + (-\varepsilon_L) = 0 \Longrightarrow \varepsilon - L\,(dI/dt) = 0$ Kirchhoff's loop law

$L\,dI = \varepsilon\,dt = \varepsilon_0 \sin \omega t\,dt$

$dI = (\varepsilon_0/L) \sin \omega t\,dt$

$\int dI = (\varepsilon_0/L) \int \sin \omega t\,dt$ integrate both sides

$I = (\varepsilon_0/\omega L)\,[-\cos \omega t\,]$

$I = (\varepsilon_0/\omega L) \sin(\omega t - \pi/2) = I_0 \sin(\omega t - \pi/2)$ $-\cos \omega t = \sin(\omega t - \pi/2)$

$I_0 = \varepsilon_0/\omega L = \varepsilon_0/X_L$ (2)

$$X_L = \omega L = 2\pi f L$$

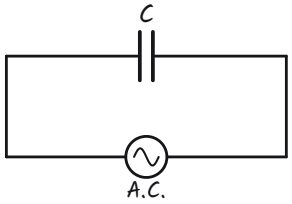
S.I. unit : ohm (Ω)

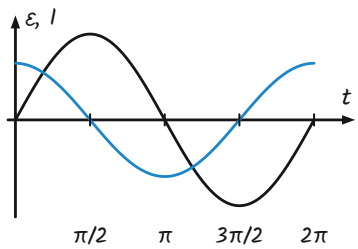
Important Concept

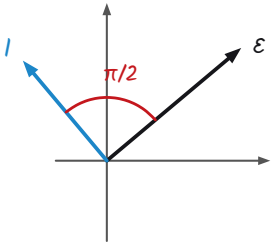
From (1) and (2): in a pure inductor the emf ε **leads** the current I by phase π/2 (current lags behind the emf by π/2). X_L is called the **inductive reactance**.

$X_L \propto f$. For D.C. ($f = 0$) $X_L = 0$, so an inductor passes D.C. easily but opposes high-frequency A.C.

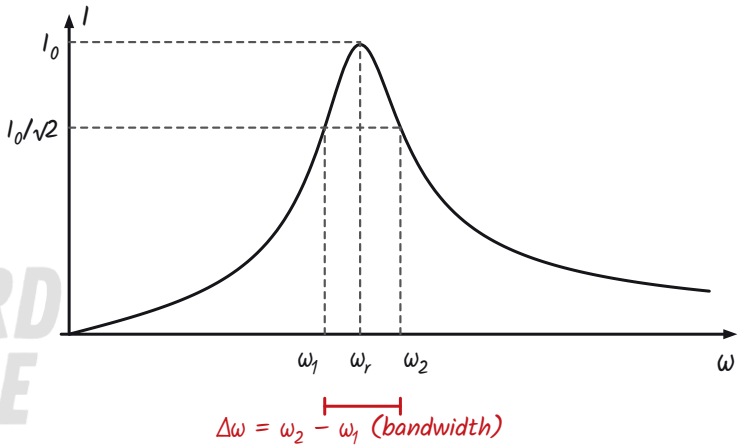
A.C. Circuit Containing Only a Capacitor







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Properties of a series LCR circuit at resonance

- $X_L = X_C$ and $\omega L = 1/\omega C$.
- $\omega_r = 1/\sqrt{LC}$, $f_r = 1/(2\pi\sqrt{LC})$.
- Current is maximum and impedance is minimum.
- $Z = \sqrt{R^2 + (X_L - X_C)^2}$ gives **$Z = R$**.
- The circuit behaves as a purely resistive circuit.
- ε and I have no phase difference: $\cos\phi = R/Z = 1$, so $\phi = 0°$.
- Average power $P_{av} = I_{eff}\varepsilon_{eff} = \varepsilon_{eff}^2/R = I_{eff}^2 R$ (maximum power).

Exam Point of View

Q. Why is a series LCR circuit at resonance called a frequency-accepting (acceptor) circuit?

Ans. At resonance $X_L = X_C$, so the impedance is minimum ($Z = R$) and the current is maximum. Away from resonance the impedance increases and the current becomes smaller, so the circuit strongly favours (selects) the frequencies close to $f_r = 1/(2\pi\sqrt{LC})$. The band of frequencies that still gives a large current is the bandwidth: the larger the Q-factor, the narrower the band and the better the selectivity. This is how a radio tunes to one station.

Quality Factor (Q-factor)

Q-factor :- The quality factor (sharpness factor) is the ratio of the angular frequency at resonance to the bandwidth. It is a unitless quantity.

$$Q = \frac{\omega_r}{\text{Bandwidth}} = \frac{\omega_r}{\omega_2 - \omega_1}$$

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Class 12 Physics | Chapter 8

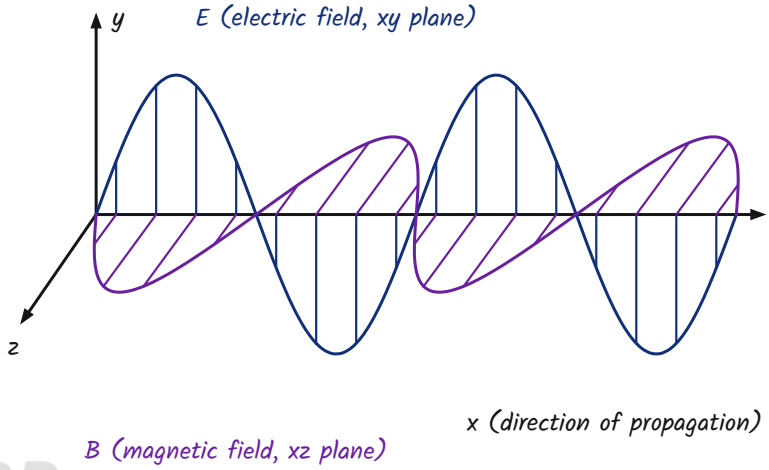
Electromagnetic Waves

Concept of EM Waves

Maxwell predicted that an **accelerated charged particle produces radiation in the form of waves**, known as electromagnetic waves. Their existence was later confirmed experimentally by Hertz.

EM waves :- A type of wave in which the **electric field and the magnetic field oscillate perpendicular to each other** (and perpendicular to the direction of propagation), with **no phase difference** ($\phi = 0$), i.e. they are in the same phase.

Graphical representation



The electric field E oscillates along the y-axis (xy plane) and the magnetic field B along the z-axis (xz plane), while the wave travels along the x-axis. So EM waves are **transverse** in nature.

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SOLVED NUMERICAL 8

An object is 30 cm in front of a concave lens of focal length 15 cm. Find the position and magnification of the image.

GIVEN DATA $u = -30$ cm , $f = -15$ cm

REQUIRED QUANTITY v and m

RELEVANT FORMULA $\frac{1}{v} - \frac{1}{u} = \frac{1}{f}$, $m = \frac{v}{u}$

SUBSTITUTION

$$\frac{1}{v} = \frac{1}{-15} + \frac{1}{-30}$$

STEP-BY-STEP CALCULATION

$$\frac{1}{v} = -\frac{2+1}{30} = -\frac{1}{10}$$

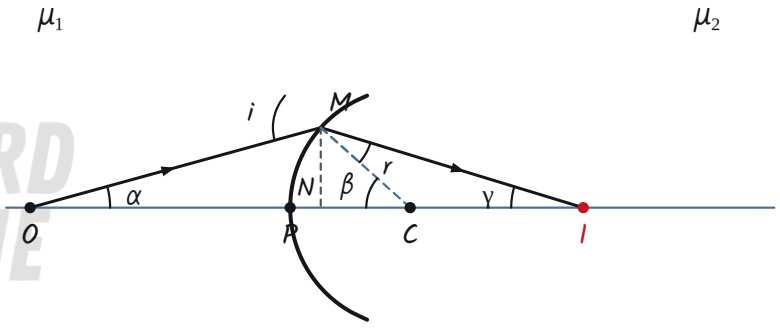
$$v = -10 \text{ cm}$$

$$m = \frac{-10}{-30} = +\frac{1}{3}$$

FINAL ANSWER **v = −10 cm , m = +1/3** virtual, erect and diminished image on the same side as the object

Refraction at a Spherical Surface

A convex spherical surface separates a rarer medium of refractive index μ_1 from a denser medium μ_2 ($\mu_2 > \mu_1$). A point object O lies on the principal axis and its image is formed at I. P is the pole and C the centre of curvature of the surface. A ray OM strikes the surface at M and is refracted along MI. Let MN be the perpendicular on the axis. The rays are taken close to the axis (**paraxial rays**), so all the angles are small.



$i = \alpha + \beta$ exterior angle of ΔOMC

$\beta = r + \gamma \Rightarrow r = \beta - \gamma$ exterior angle of ΔMCI

derivation continues on the next page

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SOLVED NUMERICAL 13 (continued)

STEP-BY-STEP CALCULATION

$$\mu = \frac{0.7071}{0.5} = 1.414$$

$$\sin i = 0.75 \Rightarrow i = 48.6°$$

$$\delta_m = 2 \times 48.6° - 60° = 37.2°$$

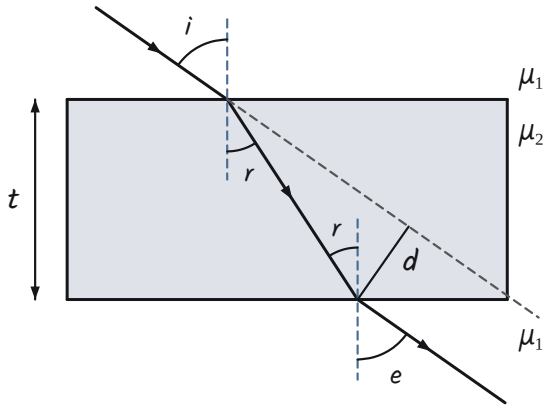
FINAL ANSWER

$\mu = \sqrt{2} = 1.414$ for $\delta_m = 30°$

$\delta_m = 37.2°$ if $\mu = 1.5$

Lateral Shift of Light through a Glass Slab

A ray of light is incident on a parallel-sided glass slab of thickness t and refractive index μ. It is refracted at the first face, travels through the glass and emerges from the opposite face **parallel to the incident ray** (since e = i), but **displaced sideways**. This perpendicular distance d between the original line of the incident ray and the emergent ray is the **lateral shift**.



$$\frac{\sin i}{\sin r} = \mu, \quad \frac{\sin r}{\sin e} = \frac{1}{\mu}$$

Snell's law at the two faces

$$\sin e = \sin i \Rightarrow e = i$$

multiplying : the emergent ray is parallel to the incident ray

$$\text{length of the path in glass} = \frac{t}{\cos r}$$

from the right-angled triangle in the slab

$$d = \frac{t}{\cos r} \sin(i - r)$$

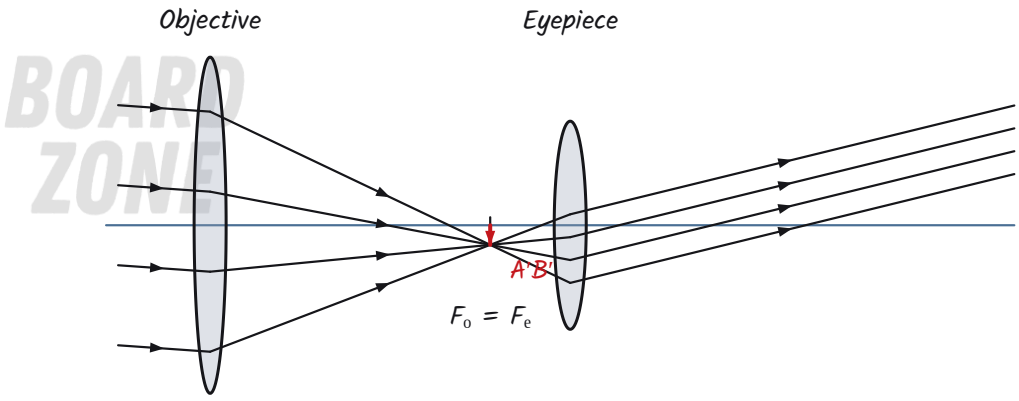
d is the perpendicular from the exit point on the original ray, and the angle between the two rays is (i − r)

$$d = \frac{t \sin(i - r)}{\cos r}$$

lateral shift

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Rays from a distant object are practically parallel. The objective forms a **real, inverted, diminished** image A′B′ at its focus F_o. The eyepiece is adjusted so that this image lies at its focus too (F_o and F_e coincide). The final image is formed at **infinity**, which is the **normal adjustment** (the eye remains relaxed).



$$m = \frac{\beta}{\alpha} \approx \frac{\tan\beta}{\tan\alpha}$$

angular magnification : angle subtended by the final image / by the object

$$\tan\alpha = \frac{A'B'}{f_o} \ , \ \tan\beta = \frac{A'B'}{f_e}$$

the intermediate image A′B′ is at the focus of both lenses

$$m = \frac{A'B'/f_e}{A'B'/f_o}$$

dividing

$$m = \frac{f_o}{f_e} \ , \ L = f_o + f_e$$

magnifying power and length of the telescope in normal adjustment

- A larger f_o and a smaller f_e give a larger magnification.
- If the final image is formed at the near point, $m = \frac{f_o}{f_e}\left(1 + \frac{f_e}{D}\right)$ and $L = f_o + u_e$ with $|u_e| < f_e$.

SOLVED NUMERICAL 17

An astronomical telescope has an objective of focal length 100 cm and an eyepiece of focal length 5 cm. Find the magnifying power and the length of the telescope in normal adjustment.

GIVEN DATA $f_o = 100$ cm , $f_e = 5$ cm

REQUIRED QUANTITY m and L

solution continues on the next page

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Intensity

The intensity of a wave is proportional to the **square of its amplitude** : $I \propto A^2$, so $I = KA^2$.

$$A^2 = A_1^2 + A_2^2 + 2A_1A_2\cos\phi$$ result for the amplitude

$$\frac{I}{K} = \frac{I_1}{K} + \frac{I_2}{K} + 2\sqrt{\frac{I_1}{K}}\sqrt{\frac{I_2}{K}}\cos\phi$$ put $A^2 = I/K$, $A_1^2 = I_1/K$, $A_2^2 = I_2/K$

$$I = I_1 + I_2 + 2\sqrt{I_1I_2}\cos\phi$$

multiply by K

	Constructive ($\phi = 0°$)	Destructive ($\phi = 180°$)
Resultant intensity	$I_{max} = I_1 + I_2 + 2\sqrt{I_1I_2} = (\sqrt{I_1} + \sqrt{I_2})^2$	$I_{min} = I_1 + I_2 - 2\sqrt{I_1I_2} = (\sqrt{I_1} - \sqrt{I_2})^2$

Comparison of Intensity at Maxima and Minima

$$I_{max} = K(A_1 + A_2)^2$$

$$I_{min} = K(A_1 - A_2)^2$$

$$\frac{I_{max}}{I_{min}} = \frac{(A_1 + A_2)^2}{(A_1 - A_2)^2}$$ dividing

Important Concept

If the two interfering waves have **equal amplitude** ($A_1 = A_2 = A$, as in Young's experiment) :

$$I_{max} = K(A + A)^2 = 4KA^2 = 4I_0 \text{ , } I_{min} = 0$$

The minima are **perfectly dark**, so the contrast between bright and dark fringes is best.

SOLVED NUMERICAL 3

Two waves of amplitudes 3 units and 4 units interfere. Find the resultant amplitude when the phase difference is (i) 0° , (ii) 90° and (iii) 180°.

GIVEN DATA $A_1 = 3$, $A_2 = 4$, $\phi = 0°$, $90°$, $180°$

REQUIRED QUANTITY Resultant amplitude A

RELEVANT FORMULA $A = \sqrt{A_1^2 + A_2^2 + 2A_1A_2\cos\phi}$

SUBSTITUTION $A = \sqrt{9 + 16 + 24\cos\phi}$

solution continues on the next page

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Fringe Width and Intensity Curve

$$\beta_0 = \frac{\lambda D}{a} - \left(-\frac{\lambda D}{a}\right)$$

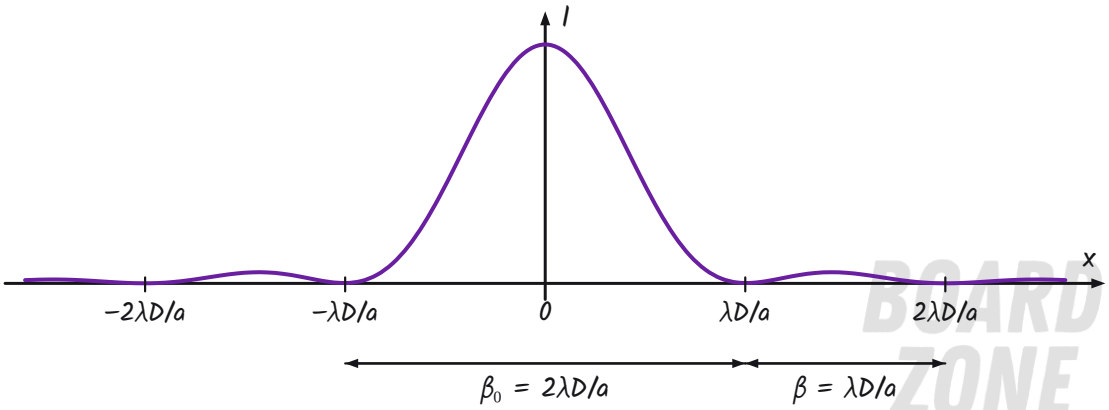
central maximum lies between the first minima on the two sides

$$\beta = \frac{n\lambda D}{a} - \frac{(n-1)\lambda D}{a}$$

secondary fringe : between two consecutive minima

$$\beta_0 = \frac{2\lambda D}{a} \ , \ \beta = \frac{\lambda D}{a}$$

central fringe width $\beta_0 = 2\beta$



	YDSE (interference)	Single slit (diffraction)
Fringe width	all fringes equal : $\beta = \frac{\lambda D}{d}$	central : $\beta_0 = \frac{2\lambda D}{a}$, others : $\beta = \frac{\lambda D}{a}$
Intensity of bright fringes	all nearly equal	falls rapidly away from the centre
Positions	bright at $n\lambda$, dark at $(2n-1)\lambda/2$	dark at $n\lambda$, bright at $(2n+1)\lambda/2$

SOLVED NUMERICAL 11

A single slit of width 0.2 mm is illuminated by light of wavelength 600 nm. The screen is 1 m from the slit. Find (i) the position of the first dark fringe and (ii) the width of the central bright fringe.

GIVEN DATA $a = 0.2\ mm = 2 \times 10^{-4}\ m$, $\lambda = 600\ nm = 6 \times 10^{-7}\ m$, $D = 1\ m$

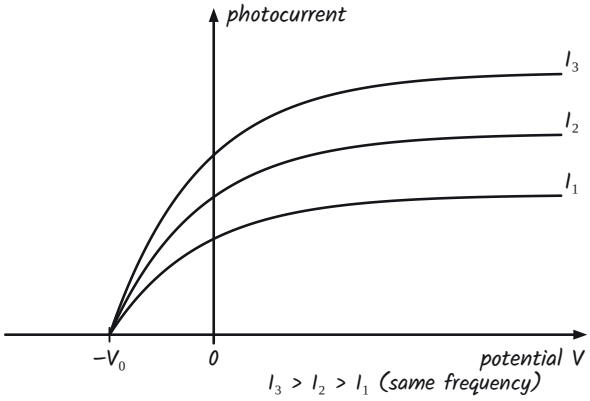
REQUIRED QUANTITY x_1 and β_0

solution continues on the next page

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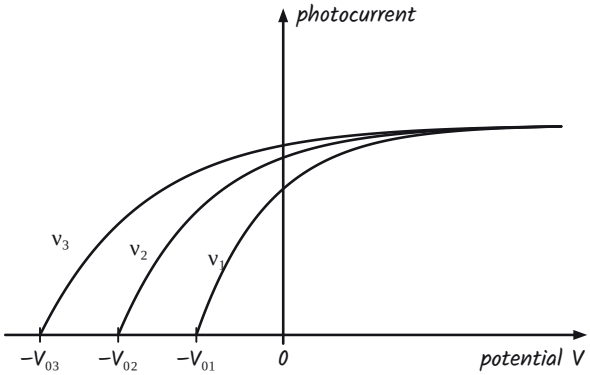
Photocurrent versus potential

Constant frequency, different intensity. The kinetic energy of the ejected electrons is the same, so the **stopping potential is the same**. But the number of electrons per second is different, so the saturation photocurrent is different : the more the intensity, the greater the saturation current.



$I_3 > I_2 > I_1$ (same frequency)

Constant intensity, different frequency. The saturation current is the **same**, but the stopping potential is **different** : the higher the frequency, the more negative the stopping potential.



$\nu_3 > \nu_2 > \nu_1$ (same intensity)

SOLVED NUMERICAL 1

Light of wavelength 4000 Å falls on a metal of work function 2.0 eV. Find (a) the energy of a photon, (b) the maximum kinetic energy of the photoelectrons, (c) the stopping potential and (d) the threshold wavelength. (hc = 12400 eV Å)

GIVEN DATA λ = 4000 Å , W_0 = 2.0 eV

REQUIRED QUANTITY E, K.E.max, V_0, λ_0

solution continues on the next page

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Forms of the de Broglie wavelength

$$\lambda = \frac{h}{mv} = \frac{h}{p} \qquad (1)\ p = mv$$

$$K.E. = \frac{1}{2}mv^2 = \frac{(mv)^2}{2m} \qquad (2)$$

$$p^2 = 2m\ K.E.,\ p = \sqrt{2m\ K.E.}$$

$$\lambda = \frac{h}{\sqrt{2m\ K.E.}}$$

$$K.E. = qV \text{ (charge } q \text{ accelerated through } V) \qquad (3)$$

$$\lambda = \frac{h}{\sqrt{2mqV}}$$

de Broglie wavelength of an electron (in terms of potential)

$$\lambda = \frac{h}{\sqrt{2meV}} \qquad q = e$$

$$\lambda = \frac{6.63 \times 10^{-34}}{\sqrt{2 \times 9.1 \times 10^{-31} \times 1.6 \times 10^{-19} \times V}} \qquad h = 6.63 \times 10^{-34}\ J\ s,\ m = 9.1 \times 10^{-31}\ kg,\ e = 1.6 \times 10^{-19}\ C$$

$$\lambda = \frac{6.63 \times 10^{-34}}{5.396 \times 10^{-25}\sqrt{V}}$$

$$\lambda_e = \frac{1.227}{\sqrt{V}}\ nm = \frac{12.27}{\sqrt{V}}\ \text{Å}$$

V in volts, for an electron accelerated from rest

Remember This

In $\lambda_e = \frac{1.227}{\sqrt{V}}$ the wavelength comes out in **nm**, not mm (for V = 100 V, λ = 0.1227 nm = 1.227 Å).

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SOLVED NUMERICAL 1

An α-particle of kinetic energy 5 MeV is fired at a gold nucleus ($Z = 79$). Find the distance of closest approach. ($k = 9 \times 10^9$ N m² C⁻², $e = 1.6 \times 10^{-19}$ C)

GIVEN DATA K.E. = 5 MeV = $5 \times 1.6 \times 10^{-13}$ J, $Z = 79$

REQUIRED QUANTITY Distance of closest approach r_0

RELEVANT FORMULA $K.E. = \frac{k(2e)(Ze)}{r_0}$, so $r_0 = \frac{2Zke^2}{K.E.}$

SUBSTITUTION

$$r_0 = \frac{2 \times 79 \times 9 \times 10^9 \times (1.6 \times 10^{-19})^2}{5 \times 1.6 \times 10^{-13}}$$

STEP-BY-STEP CALCULATION

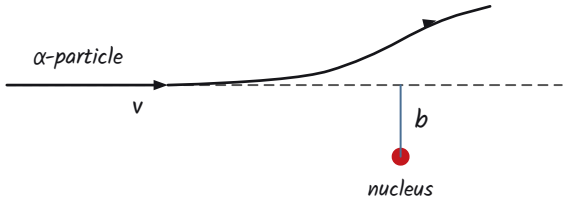
$$r_0 = \frac{2 \times 79 \times 9 \times 10^9 \times 2.56 \times 10^{-38}}{8 \times 10^{-13}}$$

$$r_0 = \frac{3.640 \times 10^{-26}}{8 \times 10^{-13}} = 4.55 \times 10^{-14} \text{ m}$$

FINAL ANSWER $r_0 \approx 4.55 \times 10^{-14}$ m
about 45.5 fm, much less than the atomic size

Impact Parameter

Impact parameter (b) :- The **perpendicular distance of the initial velocity vector of the α-particle from the central line of the nucleus.**



- For a **large** impact parameter, the force on the α-particle is weak (the force varies inversely as the square of the distance), so the deflection is **small**.
- b increases → deflection **decreases**.
- b decreases → deflection **increases**.
- b = 0 (head-on collision) → deflection is **maximum, 180°**.

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SOLVED NUMERICAL 3

Find the energy of the electron in the ground state of He^+ and in the second excited state of Li^{2+}. How much energy is needed to remove the electron from He^+ in its ground state?

GIVEN DATA $He^+ : Z = 2 , n = 1 ; Li^{2+} : Z = 3 , n = 3$ (second excited state)

REQUIRED QUANTITY Energies E

RELEVANT FORMULA $E = -13.6 \frac{Z^2}{n^2}$ eV

SUBSTITUTION

$$E_{He^+} = -13.6 \times \frac{2^2}{1^2}$$

$$E_{Li^{2+}} = -13.6 \times \frac{3^2}{3^2}$$

STEP-BY-STEP CALCULATION

$$E_{He^+} = -13.6 \times 4 = -54.4 \text{ eV}$$

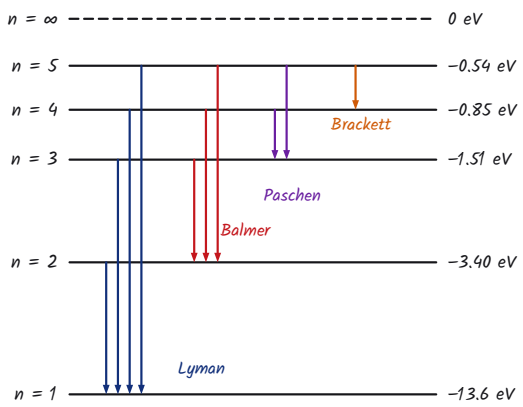
$$E_{Li^{2+}} = -13.6 \times 1 = -13.6 \text{ eV}$$

FINAL ANSWER

E (He^+, n = 1) = −54.4 eV
E (Li^{2+}, n = 3) = −13.6 eV
Ionisation energy of He^+ = 54.4 eV

Energy Level Diagram

A diagram which represents the **total energies of the electron in the different stationary orbits** of an atom is called an energy level diagram. The lowest level (n = 1) is the **ground state** and all higher levels are **excited states**. The energy of the level n = ∞ is zero.



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Important Concept

The density of nuclear matter is the **same for all nuclei** and is extremely large (about 2.3×10^{17} kg m^{-3}), about 10^{14} times the density of water. It does not depend on the mass number.

SOLVED NUMERICAL 1

Find the radius of the $^{27}_{13}Al$ nucleus and the density of nuclear matter. Take $R_0 = 1.2 \times 10^{-15}$ m and the mass of a nucleon $m = 1.66 \times 10^{-27}$ kg.

GIVEN DATA $A = 27$, $R_0 = 1.2 \times 10^{-15}$ m , $m = 1.66 \times 10^{-27}$ kg

REQUIRED QUANTITY Radius R and density ρ

RELEVANT FORMULA $R = R_0 A^{1/3}$, $\rho = \dfrac{3m}{4\pi R_0^3}$

SUBSTITUTION

$$R = 1.2 \times 10^{-15} \times (27)^{1/3}$$

$$\rho = \frac{3 \times 1.66 \times 10^{-27}}{4 \times 3.14 \times (1.2 \times 10^{-15})^3}$$

STEP-BY-STEP CALCULATION

$$R = 1.2 \times 3 = 3.6 \times 10^{-15} \text{ m}$$

$$\rho = \frac{4.98 \times 10^{-27}}{2.171 \times 10^{-44}} = 2.29 \times 10^{17} \text{ kg m}^{-3}$$

FINAL ANSWER

$R = 3.6$ fm

$\rho \approx 2.3 \times 10^{17}$ kg m^{-3} same for every nucleus

SOLVED NUMERICAL 2

The mass numbers of two nuclei are 8 and 64. Find the ratio of their nuclear radii and the ratio of their densities.

GIVEN DATA $A_1 = 8$, $A_2 = 64$

REQUIRED QUANTITY $R_1 : R_2$ and $\rho_1 : \rho_2$

RELEVANT FORMULA $R \propto A^{1/3}$, density is independent of A

SUBSTITUTION

$$\frac{R_1}{R_2} = \left(\frac{8}{64}\right)^{1/3}$$

STEP-BY-STEP CALCULATION

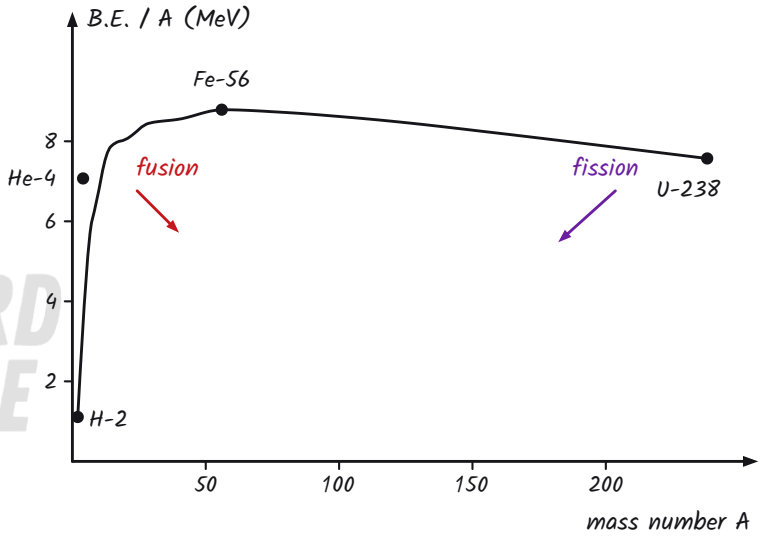
$$\frac{R_1}{R_2} = \left(\frac{1}{8}\right)^{1/3} = \frac{1}{2}$$

FINAL ANSWER

$R_1 : R_2 = 1 : 2$

$\rho_1 : \rho_2 = 1 : 1$ density is the same

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- For light nuclei ($A < 20$) B.E./A is small and rises steeply. Helium $^{4}_{2}He$ is exceptionally stable (7.07 MeV).

- For A = 30 to 170 the curve is nearly flat, about **8 MeV per nucleon**, with a maximum of about **8.8 MeV** near $^{56}_{26}Fe$.

- For heavy nuclei B.E./A falls slowly (about 7.6 MeV for $^{238}_{92}U$), so they are less stable.

SOLVED NUMERICAL 3

Calculate the binding energy and the binding energy per nucleon of $^{4}_{2}He$. Atomic masses : $m(^{1}_{1}H) = 1.007825\ u$, $m_n = 1.008665\ u$, $m(^{4}_{2}He) = 4.002603\ u$. ($1\ u = 931.5\ MeV$)

GIVEN DATA $Z = 2$, $N = 2$, $A = 4$

REQUIRED QUANTITY Binding energy and B.E./A

RELEVANT FORMULA $\Delta m = [Z\,m(H) + N\,m_n] - m(He)$, $B.E. = \Delta m \times 931.5\ MeV$

SUBSTITUTION $\Delta m = (2 \times 1.007825 + 2 \times 1.008665) - 4.002603$

STEP-BY-STEP CALCULATION

$\Delta m = 4.032980 - 4.002603 = 0.030377\ u$

$B.E. = 0.030377 \times 931.5 = 28.30\ MeV$

$$\frac{B.E.}{A} = \frac{28.30}{4} = 7.07\ MeV$$

FINAL ANSWER

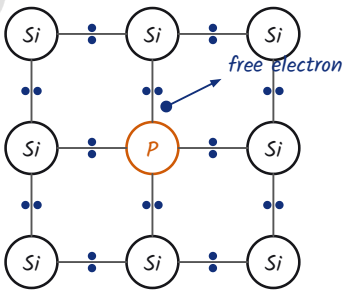
B.E. = 28.3 MeV

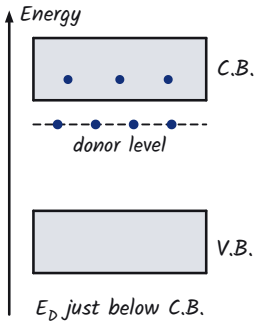
B.E./A = 7.07 MeV per nucleon

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(i) n-type Semiconductor

A pure Si (or Ge) crystal is doped with a **pentavalent** impurity (5 valence electrons) like **As, Sb, P, Bi**. Four electrons of the impurity atom form covalent bonds with four Si atoms. The **fifth electron is free** and moves to the conduction band. The impurity atom is called a **donor**, because it donates a free electron.

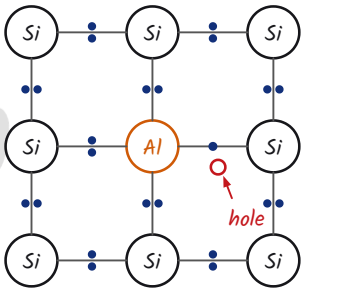


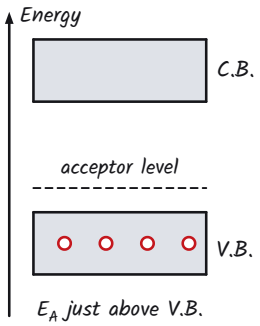


- Majority charge carriers : **electrons** ; minority carriers : **holes**. So $n_e \gg n_h$.
- The donor energy level E_D lies just **below the conduction band**, so even at room temperature almost all donor electrons jump to the conduction band.
- The crystal remains **electrically neutral**, since the donor atom becomes a positive ion and the free electron is negative.

(ii) p-type Semiconductor

A pure Si (or Ge) crystal is doped with a **trivalent** impurity (3 valence electrons) like **B, Al, In, Ga**. The impurity atom forms only three covalent bonds, so **one bond is incomplete** and a **hole** is created. The impurity atom is called an **acceptor**, because it accepts an electron from a neighbouring bond.





- Majority charge carriers : **holes** ; minority carriers : **electrons**. So $n_h \gg n_e$.
- The acceptor energy level E_A lies just **above the valence band**. Electrons from the valence band easily go to this level and leave holes in the valence band.
- This crystal is also **electrically neutral**.

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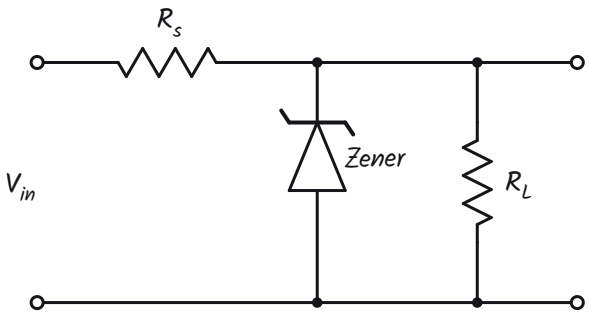
Filter and Voltage Regulation

The output of a rectifier is **pulsating DC**. A **filter** (a capacitor connected across R_L) smoothens it by removing the ripples. But the output voltage still changes if the input voltage or the load changes. A **Zener diode** is used to get a **fixed DC voltage**.



Zener diode :- A heavily doped p-n junction diode which is designed to operate in the **reverse breakdown region**. In breakdown the voltage across it stays almost **constant** (V_Z) while the current changes over a wide range.

Zener diode as a voltage regulator. The Zener diode is connected in **reverse bias** across the load R_L, with a series resistor R_s. If the input voltage increases, the extra current passes through the Zener diode and the extra voltage drops across R_s. The output voltage across the Zener diode (and R_L) stays at V_Z. If the load current changes, the Zener current changes to compensate it. So the output remains a **fixed DC voltage**.



SOLVED NUMERICAL 7

In a Zener regulator the input is 12 V, the Zener voltage is 6 V, R_s = 120 Ω and R_L = 200 Ω. Find the current through R_s, the load and the Zener diode.

GIVEN DATA $V_{in} = 12\ V$, $V_Z = 6\ V$, $R_s = 120\ \Omega$, $R_L = 200\ \Omega$

REQUIRED QUANTITY I_s , I_L and I_Z

RELEVANT FORMULA $I_s = \frac{V_{in} - V_Z}{R_s}$, $I_L = \frac{V_Z}{R_L}$, $I_Z = I_s - I_L$

solution continues on the next page

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