

CBSE Class 12 Physics Question Paper 2023 with Solution PDF-Set 55/1/1



Question Paper with Solutions

Conducted by the Central Board of Secondary Education (CBSE)

Time Allowed: 3 hours

Maximum Marks: 70

General Instructions

- (i) This question paper contains **35** questions. **All** questions are **compulsory**.
- (ii) This question paper is divided into **five** Sections – **A, B, C, D and E**.
- (iii) In **Section A** – Questions no. **1 to 18** are Multiple Choice (MCQ) type questions, carrying **1** mark each.
- (iv) In **Section B** – Questions no. **19 to 25** are Very Short Answer (VSA) type questions, carrying **2** marks each.
- (v) In **Section C** – Questions no. **26 to 30** are Short Answer (SA) type questions, carrying **3** marks each.
- (vi) In **Section D** – Questions no. **31 to 33** are Long Answer (LA) type questions carrying **5** marks each.
- (vii) In **Section E** – Questions no. **34 and 35** are case-based questions carrying **4** marks each.
- (viii) There is no overall choice. However, an internal choice has been provided in 2 questions in Section B, 2 questions in Section C, 3 questions in Section D and 2 questions in Section E.
- (ix) Use of calculators is **not** allowed.

Use the following values of physical constants, if required :

$$c = 3 \times 10^8 \text{ m/s}$$

$$h = 6.63 \times 10^{-34} \text{ Js}$$

$$e = 1.6 \times 10^{-19} \text{ C}$$

$$\mu_0 = 4\pi \times 10^{-7} \text{ T m A}^{-1}$$

$$\epsilon_0 = 8.854 \times 10^{-12} \text{ C}^2 \text{ N}^{-1} \text{ m}^{-2}$$

$$\frac{1}{4\pi\epsilon_0} = 9 \times 10^9 \text{ N m}^2 \text{ C}^{-2}$$

$$\text{Mass of electron } (m_e) = 9.1 \times 10^{-31} \text{ kg}$$

$$\text{Mass of neutron} = 1.675 \times 10^{-27} \text{ kg}$$

$$\text{Mass of proton} = 1.673 \times 10^{-27} \text{ kg}$$

$$\text{Avogadro's number} = 6.023 \times 10^{23} \text{ per gram mole}$$

$$\text{Boltzmann constant} = 1.38 \times 10^{-23} \text{ JK}^{-1}$$

Section A (18 marks)

1. A point charge situated at a distance r from a short electric dipole on its axis, experiences a force $\vec{F}$. If the distance of the charge is $2r$, the force on the charge will be: [1 mark]

- (A) $\frac{\vec{F}}{16}$
- (B) $\frac{\vec{F}}{8}$
- (C) $\frac{\vec{F}}{4}$
- (D) $\frac{\vec{F}}{2}$

Correct Answer: (B) $\frac{\vec{F}}{8}$

Solution:

Concept:

- On the axis of a short electric dipole, the electric field has magnitude $E = \frac{1}{4\pi\epsilon_0} \frac{2p}{r^3}$, where p is the dipole moment and r is the distance from its centre.
- The force on a fixed point charge q is $\vec{F} = q\vec{E}$; hence its magnitude varies as r^{-3} .

Step 1: Form the ratio of forces The dipole moment and the point charge remain unchanged. At twice the axial distance, the same dipole approximation gives

$$\frac{F'}{F} = \frac{r^3}{(2r)^3} = \frac{1}{8}.$$

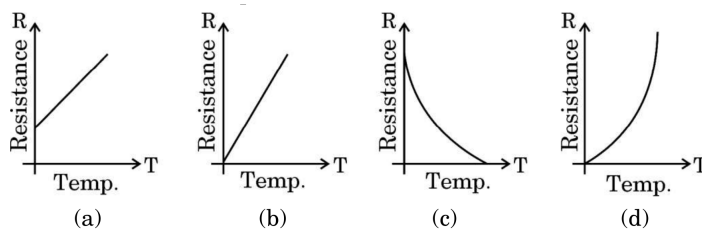
Step 2: Check the direction and alternatives Moving outward along the same axis does not reverse the field, so the force retains its direction. The factors $1/16$, $1/4$ and $1/2$ would require inverse fourth-power, inverse-square and inverse-distance laws respectively. None describes the axial field of a short dipole.

Step 3: Conclusion The new force is $\vec{F}' = \vec{F}/8$. Hence, the correct option is (B).

Quick Tip to Solve: For a short dipole's electric field, cube the distance multiplier: doubling the distance divides the force on a fixed charge by eight.

2. For a metallic conductor, the correct representation of variation of resistance R with temperature T is:

[1 mark]



(A) Graph (a)

(B) Graph (b)

(C) Graph (c)

(D) Graph (d)

Correct Answer: (A) Graph (a)

Solution:

Concept:

- Over the usual moderate temperature range, the resistance of a metal obeys $R = R_0[1 + \alpha(T - T_0)]$, where R_0 is its resistance at reference temperature T_0 .
- A metallic conductor has positive temperature coefficient α : stronger lattice vibrations increase electron scattering and resistance as temperature rises.

Step 1: Identify the slope and intercept Taking the temperature scale relative to the reference zero, the law has the form $R = R_0 + \alpha R_0 T$. Thus the graph is approximately straight with positive slope and a finite resistance at the temperature origin used in this elementary representation. Graph (a) has both features.

Step 2: Compare the remaining graphs Graph (b) passes through the origin and would imply zero resistance at this temperature origin. Graph (c) shows decreasing resistance, contrary to the positive coefficient of an ordinary metal. Graph (d) is strongly curved upward rather than following the standard approximate linear variation. The linear law is not an extrapolation to absolute zero.

Step 3: Conclusion Graph (a) represents the usual variation of metallic resistance with temperature. Hence, the correct option is (A).

Quick Tip to Solve: For the standard metal resistance graph, check both a positive slope and a nonzero reference resistance; slope alone cannot distinguish (a) from (b).

3. The potential difference across a cell in an open circuit is 8 V. It falls to 4 V when a current of 4 A is drawn from it. The internal resistance of the cell is: [1 mark]

- (A) $4\ \Omega$
- (B) $3\ \Omega$
- (C) $2\ \Omega$
- (D) $1\ \Omega$

Correct Answer: (D) $1\ \Omega$

Solution:

Concept:

- The open-circuit terminal potential difference equals the emf $\mathcal{E}$, because no current flows and there is no internal voltage drop.
- When a cell supplies current I , its terminal voltage is $V = \mathcal{E} - Ir$, where r is its internal resistance.

Step 1: Find the internal voltage drop The emf is 8 V, while the loaded terminal voltage is 4 V. The lost voltage inside the cell is therefore

$$Ir = \mathcal{E} - V = 8 - 4 = 4\text{ V.}$$

Step 2: Divide by the supplied current The current is 4 A, so

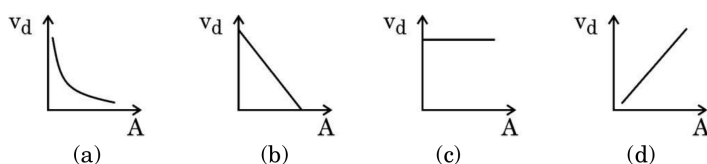
$$r = \frac{\mathcal{E} - V}{I} = \frac{4}{4} = 1\ \Omega.$$

As a check, $4\ \Omega$, $3\ \Omega$ and $2\ \Omega$ would cause internal drops of 16 V, 12 V and 8 V, respectively, at this current. None matches the observed drop of 4 V.

Step 3: Conclusion The cell's internal resistance is $1\ \Omega$. Hence, the correct option is (D).

Quick Tip to Solve: First subtract the loaded voltage from the open-circuit voltage; divide that voltage loss by current to obtain internal resistance.

4. A steady current flows through a metallic wire whose area of cross-section (A) increases continuously from one end of the wire to the other. The magnitude of drift velocity (v_d) of the free electrons as a function of ' A ' can be shown by: [1 mark]



- (A) Graph (a)
 (B) Graph (b)
 (C) Graph (c)
 (D) Graph (d)

Correct Answer: (A) Graph (a)

Solution:

Concept:

- In a metallic conductor, current is $I = neAv_d$, where n is the free-electron number density, e the magnitude of electron charge, A the cross-sectional area and v_d the drift speed.
- In steady flow, charge does not accumulate in any section of a continuous wire, so the same current passes through every cross-section.

Step 1: Express drift speed in terms of area The material has constant free-electron density. Since I , n and e are fixed along the wire,

$$v_d = \frac{I}{neA}, \quad Av_d = \frac{I}{ne} = \text{constant}.$$

Hence, a larger area allows the same charge per second to pass with a smaller drift speed.

Step 2: Identify the shape of the graph An inverse relation gives a decreasing rectangular hyperbola, as in graph (a). Graph (b) decreases linearly and reaches zero at a finite area, which the formula does not permit. Graph (c) would imply constant drift speed, and graph (d) an increasing drift speed; both contradict current continuity for this wire.

Step 3: Conclusion Drift speed varies inversely with cross-sectional area, as shown by graph (a). Hence, the correct option is (A).

Quick Tip to Solve: In a steady current through one wire, use $Av_d = \text{constant}$: doubling the area halves the drift speed, so choose a hyperbola.

5. A diamagnetic substance is brought near the north or south pole of a bar magnet. It will be:

[1 mark]

- (A) repelled by both the poles.
- (B) attracted by both the poles.
- (C) repelled by the north pole and attracted by the south pole.
- (D) attracted by the north pole and repelled by the south pole.

Correct Answer: (A) repelled by both the poles.

Solution:

Concept:

- A diamagnetic substance has a small negative magnetic susceptibility χ_m . Its induced magnetisation $\vec{M} = \chi_m \vec{H}$ opposes the applied magnetic field $\vec{H}$.
- In a nonuniform magnetic field, a diamagnetic material tends to move from the stronger-field region towards the weaker-field region.

Step 1: Consider the substance near either pole The magnetic field is stronger close to either pole of a bar magnet. The induced response opposes that field, so the substance tends to move away from the nearby pole towards weaker field. This explains repulsion without assigning a permanent pole to the substance.

Step 2: Check what happens when the pole reverses Changing the north pole to the south pole reverses the local applied field and also reverses the induced magnetisation. Their opposing relationship remains unchanged. Thus the attraction in option (B) is inappropriate for a diamagnet, and the different behaviours at the two poles in (C) and (D) are also incorrect.

Step 3: Conclusion The diamagnetic substance is repelled by both poles. Hence, the correct option is (A).

Quick Tip to Solve: Remember that a diamagnet seeks weaker field near either magnetic pole; reversing the applied field also reverses its induced magnetisation.

6. A circular coil of radius 8.0 cm and 40 turns is rotated about its vertical diameter with an angular speed of $\frac{25}{\pi} \text{ rad s}^{-1}$ in a uniform horizontal magnetic field of magnitude $3.0 \times 10^{-2} \text{ T}$. The maximum emf induced in the coil is:

[1 mark]

- (A) 0.12 V
- (B) 0.15 V
- (C) 0.19 V
- (D) 0.22 V

Correct Answer: (C) 0.19 V

Solution:

Concept:

- For a coil of N turns and area A rotating in a uniform magnetic field B , flux linkage is $NBA \cos \omega t$, with a suitable choice of time origin.
- Faraday's law gives $\varepsilon = NBA\omega \sin \omega t$, so the maximum magnitude is $\varepsilon_0 = NBA\omega$.

Step 1: Convert the radius and find the area The radius is $8.0 \text{ cm} = 0.080 \text{ m}$. Therefore

$$A = \pi r^2 = \pi(0.080)^2 = 0.0064\pi \text{ m}^2.$$

The printed angular speed is $25/\pi \text{ rad s}^{-1}$, so its denominator must be retained.

Step 2: Calculate and compare the peak emf Substituting $N = 40$ and $B = 3.0 \times 10^{-2} \text{ T}$,

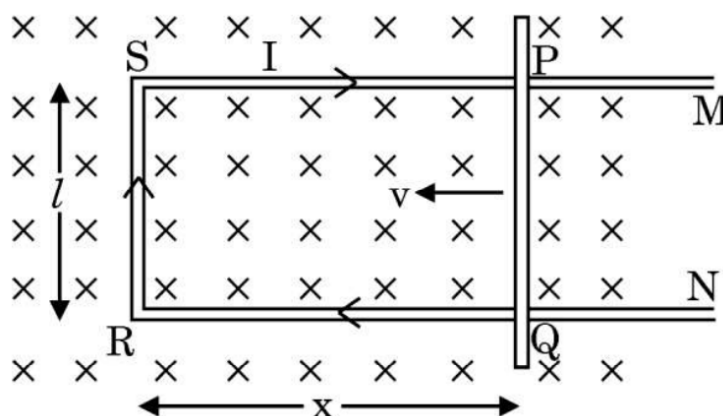
$$\varepsilon_0 = 40(3.0 \times 10^{-2})(0.0064\pi) \frac{25}{\pi} = 0.192 \text{ V}.$$

The factor π cancels. Rounding to two significant figures gives 0.19 V ; the alternatives 0.12 V , 0.15 V and 0.22 V do not match this product. The question asks for the peak, so no root-mean-square factor is needed.

Step 3: Conclusion The maximum induced emf is 0.19 V . Hence, the correct option is (C).

Quick Tip to Solve: Keep $A = \pi r^2$ symbolic until multiplying by the printed $25/\pi$; the cancellation makes this calculation immediate.

7. Figure shows a rectangular conductor $PSRQ$ in which movable arm PQ has a resistance r and resistance of $PSRQ$ is negligible. The magnitude of emf induced when PQ is moved with a velocity $\vec{v}$ does not depend on: [1 mark]



- (A) magnetic field ($\vec{B}$)
- (B) velocity ($\vec{v}$)
- (C) resistance (r)
- (D) length of PQ

Correct Answer: (C) resistance (r)

Solution:

Concept:

- A straight conductor of length l , moving with speed v perpendicular to its length and a uniform magnetic field B , develops motional emf $\varepsilon = Blv$.
- Faraday's law gives the same result, $|\varepsilon| = |d\Phi_B/dt|$. Circuit resistance determines the induced current after the emf is established.

Step 1: Find the rate of change of magnetic flux Let l be the length of PQ and x the distance from it

to the fixed arm SR. The loop area is lx , so the flux magnitude is Blx . As PQ moves with speed v ,

$$|\varepsilon| = Bl \left| \frac{dx}{dt} \right| = Blv.$$

The direction of motion determines the polarity but not this magnitude formula.

Step 2: Separate emf from current The formula contains the magnetic field, speed and rod length, so options (A), (B) and (D) each describe a quantity on which the emf depends. Resistance does not occur in the flux-change expression. With all other resistance negligible, the current is $I = Blv/r$, so changing r changes the current for the stated motion, while the induced emf remains fixed.

Step 3: Conclusion The induced emf does not depend on the resistance r . Hence, the correct option is (C).

Quick Tip to Solve: Distinguish $\varepsilon = Blv$ from $I = Blv/r$: resistance appears only when converting the motional emf into circuit current.

8. In the process of charging of a capacitor, the current produced between the plates of the capacitor is (where symbols have their usual meanings): [1 mark]

- (A) $\mu_0 \frac{d\phi_E}{dt}$
- (B) $\frac{1}{\mu_0} \frac{d\phi_E}{dt}$
- (C) $\varepsilon_0 \frac{d\phi_E}{dt}$
- (D) $\frac{1}{\varepsilon_0} \frac{d\phi_E}{dt}$

Correct Answer: (C) $\varepsilon_0 \frac{d\phi_E}{dt}$

Solution:

Concept:

- A changing electric field produces displacement current. In vacuum, Maxwell's expression is $I_d = \varepsilon_0 \frac{d\phi_E}{dt}$, where $\phi_E = \int \vec{E} \cdot d\vec{A}$ is electric flux.
- Between the plates of an ideal charging capacitor, no conduction charge crosses the insulating gap, but the changing electric flux supplies displacement current equal to the charging current.

Step 1: Relate electric flux to plate charge For parallel plates of area A , neglecting edge effects, the electric field is $E = Q/(\varepsilon_0 A)$. Hence

$$\phi_E = EA = \frac{Q}{\varepsilon_0}.$$

As the capacitor charges, Q and therefore the electric flux between the plates change with time.

Step 2: Differentiate and identify the coefficient Differentiating gives

$$\varepsilon_0 \frac{d\phi_E}{dt} = \frac{dQ}{dt} = I.$$

This identifies the displacement current in the gap. The factors μ_0 and $1/\mu_0$ in (A) and (B) do not follow from the electric-flux relation. Option (D) incorrectly divides by ε_0 , rather than multiplying by it.

Step 3: Conclusion The current between the plates is $I_d = \varepsilon_0 \frac{d\phi_E}{dt}$. Hence, the correct option is (C).

Quick Tip to Solve: Use $\varepsilon_0 \phi_E = Q$ and differentiate: this immediately gives the correct coefficient in the displacement-current formula.

9. For a concave mirror of focal length f , the minimum distance between the object and its real image is: [1 mark]

- (A) zero
- (B) f
- (C) $2f$
- (D) $4f$

Correct Answer: (A) zero

Solution:

Concept:

- For a spherical mirror, $1/f = 1/u + 1/v$, where u , v and f are signed object distance, image distance and focal length.
- A concave mirror forms a real, inverted image at its centre of curvature when the object is placed there; object and image then share the same axial position.

Step 1: Place the object at the centre of curvature Let $F = |f|$ be the positive focal-length magnitude. At the centre of curvature, $u = -2F$ and $f = -F$. The mirror formula gives

$$\frac{1}{v} = -\frac{1}{F} + \frac{1}{2F} = -\frac{1}{2F}, \quad v = -2F.$$

The negative image distance confirms a real image in front of the mirror.

Step 2: Compare the object and image positions The axial separation is $|u - v| = |-2F - (-2F)| = 0$. A distance cannot be negative, so this attainable value is the minimum. The positive values f , $2f$ and $4f$ in the other options cannot be the minimum. In particular, adding the distances from the mirror would incorrectly give $4F$.

Step 3: Conclusion The minimum distance between object and its real image is zero. Hence, the correct option is (A).

Quick Tip to Solve: For minimum object-image separation with a concave mirror, test the centre of curvature, where object and image coincide axially.

10. The radius of the n^{th} orbit in Bohr model of hydrogen atom is proportional to:

[1 mark]

- (A) $\frac{1}{n^2}$
- (B) $\frac{1}{n}$
- (C) n^2
- (D) n

Correct Answer: (C) n^2

Solution:

Concept:

- In Bohr's hydrogen atom, the electrostatic attraction supplies centripetal force: $m_e v^2 / r = k e^2 / r^2$, with $k = 1 / (4\pi\epsilon_0)$.
- Angular momentum is quantised: $m_e v r = n \hbar$, where n is the principal quantum number and $\hbar = h / (2\pi)$.

Step 1: Eliminate the orbital speed From angular-momentum quantisation, $v = n \hbar / (m_e r)$. Substitution into the force equation gives

$$\frac{n^2 \hbar^2}{m_e r^3} = \frac{k e^2}{r^2}.$$

Multiplying by r^3 isolates the radius without assuming that the electron speed is fixed.

Step 2: Identify the dependence on quantum number Rearranging,

$$r_n = \frac{\hbar^2}{m_e k e^2} n^2 = a_0 n^2.$$

Here a_0 is the constant Bohr radius. Thus doubling n makes the radius four times larger. The inverse dependences in (A) and (B) predict shrinking orbits, while (D) predicts only linear growth; none matches this result.

Step 3: Conclusion The radius is proportional to n^2 . Hence, the correct option is (C).

Quick Tip to Solve: Remember the hydrogen scalings together: radius grows as n^2 , while binding-energy magnitude falls as $1/n^2$.

11. Hydrogen atom initially in the ground state, absorbs a photon which excites it to $n = 5$ level. The wavelength of the photon is:

[1 mark]

- (A) 975 nm
- (B) 740 nm
- (C) 523 nm
- (D) 95 nm

Correct Answer: (D) 95 nm

Solution:

Concept:

- Hydrogen has bound-state energies $E_n = -13.6/n^2$ eV, measured relative to the ionisation limit.
- Absorption requires photon energy $E_\gamma = E_f - E_i = hc/\lambda$; use $hc \simeq 1240$ eV nm.

Step 1: Calculate the excitation energy The ground state is $n_i = 1$, and the final level is $n_f = 5$. Therefore,

$$\Delta E = -\frac{13.6}{25} - (-13.6) = 13.6 \left(1 - \frac{1}{25}\right) = 13.056 \text{ eV}.$$

This positive energy is supplied by the absorbed photon; using only the final binding energy would miss the initial state's energy.

Step 2: Convert the energy to wavelength Substituting in the photon relation,

$$\lambda = \frac{1240}{13.056} \text{ nm} \simeq 95 \text{ nm}.$$

This lies in the ultraviolet, as expected for a transition involving hydrogen's ground state. The wavelengths 975, 740 and 523 nm correspond to much smaller photon energies and cannot produce this excitation.

Step 3: Conclusion The absorbed photon has wavelength approximately 95 nm. Hence, the correct option is (D).

Quick Tip to Solve: For excitation out of the ground state, first use $13.6(1 - 1/n^2)$ eV, then divide 1240 by that energy to obtain nanometres.

12. The mass density of a nucleus of mass number A is:

[1 mark]

- (A) proportional to $A^{1/3}$
- (B) proportional to $A^{2/3}$
- (C) proportional to A^3
- (D) independent of A

Correct Answer: (D) independent of A

Solution:

Concept:

- A nucleus with mass number A has approximate mass $M = Am_N$, where m_N is the mean nucleon mass.
- Nuclear radius obeys $R = R_0 A^{1/3}$, with nearly constant R_0 ; the spherical volume is $V = 4\pi R^3/3$.

Step 1: Express the nuclear volume in terms of mass number Cubing the empirical radius relation gives

$$V = \frac{4\pi}{3} \left(R_0 A^{1/3}\right)^3 = \frac{4\pi R_0^3}{3} A.$$

Thus the nuclear volume grows in direct proportion to the number of nucleons, even though its radius grows only as $A^{1/3}$.

Step 2: Divide mass by volume The mass density is

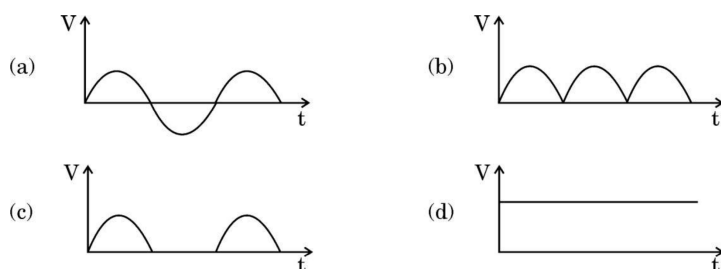
$$\rho = \frac{M}{V} = \frac{Am_N}{(4\pi R_0^3/3)A} = \frac{3m_N}{4\pi R_0^3}.$$

The factor A cancels. Hence no power of A remains: the proposed $A^{1/3}$, $A^{2/3}$ and A^3 dependences confuse density with a geometrical scaling. Small binding-energy corrections are neglected in this standard nuclear model.

Step 3: Conclusion Nuclear mass density is approximately independent of A . Hence, the correct option is (D).

Quick Tip to Solve: Cube the radius law before finding density: nuclear mass and volume both scale as A , so their ratio stays constant.

13. An ac source of voltage is connected in series with a p-n junction diode and a load resistor. The correct option for output voltage across load resistance will be: [1 mark]



- (A) Graph (a)
(B) Graph (b)
(C) Graph (c)
(D) Graph (d)

Correct Answer: (C) Graph (c)

Solution:

Concept:

- A p-n junction diode conducts readily under forward bias and offers very high resistance under reverse bias.
- The voltage across the load resistor is $V_L = IR_L$, where I is circuit current and R_L is load resistance. A single series diode acts as a half-wave rectifier.

Step 1: Follow the two input half-cycles During the forward-bias half-cycle, current passes through the diode and resistor, producing a voltage pulse across the load. During the reverse-bias half-cycle, the diode blocks current apart from negligible leakage, so $I \simeq 0$ and $V_L \simeq 0$. The output therefore has one pulse per complete input cycle.

Step 2: Compare the four waveforms Graph (c) shows positive half-cycle pulses separated by zero-voltage intervals, which is the half-wave output under the polarity shown. Graph (a) retains both signs and is unrectified ac. Graph (b) uses both half-cycles and is a full-wave output, requiring a different rectifier arrangement. Graph (d) is constant dc, which the stated unfiltered circuit cannot supply.

Step 3: Conclusion The load receives the half-wave rectified voltage shown in graph (c). Hence, the correct option is (C).

Quick Tip to Solve: With one series diode, retain alternate half-cycles and replace the intervening half-cycles by zero; do not flip them upward.

14. When an intrinsic semiconductor is doped with a small amount of trivalent impurity, then:

[1 mark]

- (A) its resistance increases.
- (B) it becomes a p-type semiconductor.
- (C) there will be more free electrons than holes in the semiconductor.
- (D) dopant atoms become donor atoms.

Correct Answer: (B) it becomes a p-type semiconductor.

Solution:

Concept:

- Pure silicon or germanium has four valence electrons and forms four covalent bonds with neighbouring atoms.
- A trivalent dopant has three valence electrons. It introduces an acceptor level and creates holes, which become the majority carriers in a p-type semiconductor.

Step 1: Identify the carrier introduced by the dopant When a trivalent atom replaces a host atom, only three of the four neighbouring covalent bonds can be completed using its own valence electrons. The electron deficiency acts as a hole. The impurity can accept an electron from the valence band, leaving a mobile hole; hence it is called an acceptor impurity.

Step 2: Test each statement about the doped material The enhanced hole concentration makes holes the majority carriers and electrons the minority carriers, so the material is p-type. Doping increases conductivity and therefore decreases resistance for the same specimen geometry, contrary to (A). There are more holes than free electrons, contrary to (C). The impurity atoms are acceptors, whereas donors are pentavalent dopants, so (D) is also false.

Step 3: Conclusion Trivalent doping produces a p-type semiconductor. Hence, the correct option is (B).

Quick Tip to Solve: Compare the dopant's three valence electrons with the host's four: one electron short means a hole and therefore p-type conduction.

15. In the energy-band diagram of n-type Si, the gap between the bottom of the conduction band E_C and the donor energy level E_D is of the order of:

[1 mark]

- (A) 10 eV
- (B) 1 eV
- (C) 0.1 eV
- (D) 0.01 eV

Correct Answer: (D) 0.01 eV

Solution:

Concept:

- In n-type silicon, a pentavalent donor introduces an allowed energy level E_D just below the conduction-band edge E_C .
- The small donor ionisation energy $\Delta E = E_C - E_D$ is the energy needed to release a donor electron into the conduction band; it is much smaller than silicon's valence-to-conduction band gap.

Step 1: Identify the energy separation being asked The question concerns the donor level and the bottom of the conduction band, not the full forbidden gap. The donor's extra electron is weakly bound and needs only a small energy to become a conduction electron. A shallow donor in silicon has a binding energy of a few hundredths of an electron volt, commonly about 0.05 eV.

Step 2: Compare the energy scales in the options A few hundredths of an electron volt is written as a coefficient of order unity times 10^{-2} eV. Thus the relevant scale is 0.01 eV. The 1 eV option instead resembles silicon's full band-gap scale; 10 eV is far too large, while 0.1 eV is the tenths rather than hundredths scale.

Step 3: Conclusion The separation $E_C - E_D$ is of the order of 0.01 eV. Hence, the correct option is (D).

Quick Tip to Solve: Distinguish the shallow donor-to-conduction separation, of hundredths of an eV, from silicon's full band gap, of about one eV.

16. Assertion (A): When a bar of copper is placed in an external magnetic field, the field lines get concentrated inside the bar.

Reason (R): Copper is a paramagnetic substance.

[1 mark]

- (A) Both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of the Assertion (A).
- (B) Both Assertion (A) and Reason (R) are true, but Reason (R) is not the correct explanation of the Assertion (A).
- (C) Assertion (A) is true, but Reason (R) is false.
- (D) Assertion (A) is false and Reason (R) is also false.

Correct Answer: (D) Assertion (A) is false and Reason (R) is also false.

Solution:

Concept:

- Diamagnetic materials develop weak induced magnetisation opposite to an applied magnetic field; their magnetic susceptibility is negative, $\chi_m < 0$.
- Copper is diamagnetic, with relative permeability slightly below unity, $\mu_r = 1 + \chi_m < 1$. Field lines are consequently less dense inside it than in the surrounding vacuum.

Step 1: Evaluate the assertion The assertion says that field lines concentrate inside a copper bar. Copper's induced magnetisation opposes the external field and weakens the field within the bar. The field lines are slightly expelled, rather than concentrated. Therefore Assertion (A) is false.

Step 2: Evaluate the reason The reason identifies copper as paramagnetic. A paramagnetic material has positive susceptibility and weak magnetisation along the applied field. Copper has the opposite response and belongs to the diamagnetic class. Therefore Reason (R) is also false.

Step 3: Test the explanatory relation Since the stated material classification is false, it cannot explain the asserted behaviour. Options (A) and (B) both require true statements, and option (C) requires a

true assertion. All three conflict with the two separate evaluations above.

Step 4: Conclusion Both the assertion and the reason are false. Hence, the correct option is (D).

Quick Tip to Solve: First classify copper as diamagnetic; then use negative susceptibility to infer weaker internal field and less crowded field lines.

17. Assertion (A): The phase difference between any two points on a wavefront is zero.

Reason (R): All points on a wavefront are at the same distance from the source and thus oscillate in the same phase. [1 mark]

- (A) Both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of the Assertion (A).
(B) Both Assertion (A) and Reason (R) are true, but Reason (R) is not the correct explanation of the Assertion (A).
(C) Assertion (A) is true, but Reason (R) is false.
(D) Assertion (A) is false and Reason (R) is also false.

Correct Answer: (A) Both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of the Assertion (A).

Solution:

Concept:

- A wavefront is the locus of points oscillating in the same phase at a given instant.
- In a homogeneous medium, equal distances from a point source correspond to equal propagation times and hence equal phases.

Step 1: Assess the assertion All points on one wavefront have the same phase by definition. Thus the phase difference between any pair of its points is zero, and Assertion (A) is true.

Step 2: Assess the reason For the usual wavefront produced by a source in a uniform medium, points at the same distance receive the disturbance after the same travel time. They therefore oscillate in phase. Reason (R) is true in this standard setting.

Step 3: Check the explanatory connection The equal travel distances give equal phases, which directly explains the zero phase difference. Option (B) incorrectly denies this connection; options (C) and (D) incorrectly reject a true statement.

Step 4: Conclusion Both A and R are true, and R correctly explains A. Hence, the correct option is (A).

Quick Tip to Solve: For a wavefront, test phase equality first; do not confuse points on one wavefront with points along a ray.

18. Assertion (A): Photoelectric effect demonstrates the particle nature of light.

Reason (R): Photoelectric current is proportional to intensity of incident radiation for frequencies more than the threshold frequency. [1 mark]

- (A) Both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of the Assertion (A).
- (B) Both Assertion (A) and Reason (R) are true, but Reason (R) is not the correct explanation of the Assertion (A).
- (C) Assertion (A) is true, but Reason (R) is false.
- (D) Assertion (A) is false and Reason (R) is also false.

Correct Answer: (B) Both Assertion (A) and Reason (R) are true, but Reason (R) is not the correct explanation of the Assertion (A).

Solution:

Concept:

- A photon of frequency ν transfers energy $h\nu$ to an electron; emission requires $h\nu \geq \phi$, where ϕ is the work function.
- At fixed frequency above threshold and fixed collecting conditions, greater intensity supplies more photons per second and increases the photoelectric current.

Step 1: Assess the assertion The threshold frequency and the relation $K_{\max} = h\nu - \phi$ are explained by localized transfers of energy in photons. The photoelectric effect thus demonstrates the particle nature of light, so A is true.

Step 2: Assess the reason With frequency above threshold, increasing intensity increases the rate of electron emission and consequently the photoelectric current under the same collection conditions. Thus R is true.

Step 3: Test whether the reason proves particle behaviour Proportionality of current to intensity alone does not establish quantized energy transfer; an increase in emitted charge with greater incident energy is not uniquely a particle prediction. The threshold and frequency dependence of maximum kinetic energy provide the decisive evidence. Hence R does not explain A; option (A) confuses a true observation with the required explanation, while (C) and (D) wrongly deny true statements.

Step 4: Conclusion Both A and R are true, but R is not the correct explanation of A. Hence, the correct option is (B).

Quick Tip to Solve: Distinguish current, which tracks intensity, from maximum electron energy, which tracks frequency and reveals photon energy.

Section B (14 marks)

19. An alpha particle is projected with velocity $\vec{V} = (3.0 \times 10^5 \text{ m/s}) \hat{i}$ into a region in which magnetic field $\vec{B} = [(0.4 \text{ T}) \hat{i} + (0.3 \text{ T}) \hat{j}]$ exists. Calculate the acceleration of the particle in the region. $\hat{i}$, $\hat{j}$ and $\hat{k}$ are unit vectors along x , y and z axis respectively and charge to mass ratio for alpha particle is $4.8 \times 10^7 \text{ C/kg}$. [2 marks]

Solution:

Concept:

- The magnetic Lorentz force is $\vec{F} = q(\vec{v} \times \vec{B})$, so the instantaneous acceleration is $\vec{a} = (q/m)(\vec{v} \times \vec{B})$.
- Only the field perpendicular to the velocity contributes: $\hat{i} \times \hat{i} = 0$ and $\hat{i} \times \hat{j} = \hat{k}$. An alpha particle has positive charge.

Step 1: Evaluate the vector product At entry the velocity is along positive x . The 0.4 T component is parallel to it and exerts no force. The 0.3 T component acts perpendicular to the velocity:

$$\begin{aligned}\vec{v} \times \vec{B} &= (3.0 \times 10^5) \hat{i} \times (0.4 \hat{i} + 0.3 \hat{j}) \\ &= (3.0 \times 10^5)(0.3) \hat{k} \\ &= 9.0 \times 10^4 \hat{k} \text{ T m s}^{-1}.\end{aligned}$$

Step 2: Apply the charge-to-mass ratio Substitute the supplied $q/m = 4.8 \times 10^7 \text{ C kg}^{-1}$:

$$\begin{aligned}\vec{a} &= (4.8 \times 10^7)(9.0 \times 10^4) \hat{k} \\ &= 4.32 \times 10^{12} \hat{k} \text{ m s}^{-2}.\end{aligned}$$

The right-hand rule gives positive z ; the positive alpha-particle charge does not reverse that direction. This is the instantaneous acceleration for the stated velocity. Its direction changes as the particle moves in the magnetic field, although the field does no work.

Step 3: Conclusion The acceleration is $\boxed{\vec{a} = 4.32 \times 10^{12} \hat{k} \text{ m s}^{-2}}$, along the positive z -axis at entry.

Quick Tip to Solve: When velocity lies along one coordinate axis, discard the parallel magnetic-field component before taking the cross product.

20. Consider an induced magnetic field due to changing electric field and an induced electric field due to changing magnetic field. Which one is more easily observed? Justify your answer. [2 marks]

Solution:

Concept:

- Faraday's law gives an electric field around a changing magnetic flux: $\oint \vec{E} \cdot d\vec{l} = -d\Phi_B/dt$, where Φ_B is magnetic flux.
- The displacement-current term of the Ampere-Maxwell law gives $\oint \vec{B} \cdot d\vec{l} = \mu_0 \epsilon_0 d\Phi_E/dt$ when conduction current is absent; Φ_E is electric flux.

Step 1: Examine electromagnetic induction A changing magnetic flux produces a circulating electric field. In a conducting loop this field drives a measurable induced current or emf. Moving a magnet relative to a coil therefore provides a simple experimental observation of the electric field induced by

a changing magnetic field.

Step 2: Examine the displacement-current effect A changing electric field also produces a magnetic field, but its coupling contains the small factor

$$\mu_0 \varepsilon_0 = \frac{1}{c^2} \simeq 1.11 \times 10^{-17} \text{ s}^2 \text{ m}^{-2}.$$

Consequently, ordinary laboratory changes of electric flux usually produce a very weak magnetic field; observing it requires sensitive apparatus or very rapid changes of electric flux. Faraday induction is readily demonstrated with a coil and galvanometer. The numerical factor is dimensionful, so this is a practical comparison of observability, not a direct comparison of electric and magnetic field magnitudes in unlike units.

Step 3: Conclusion The electric field induced by a changing magnetic field is more easily observed, through the readily measurable emf or current it produces in a coil.

Quick Tip to Solve: Compare Faraday's law with the displacement-current term; the factor $\mu_0 \varepsilon_0 = 1/c^2$ explains the weak magnetic effect in ordinary experiments.

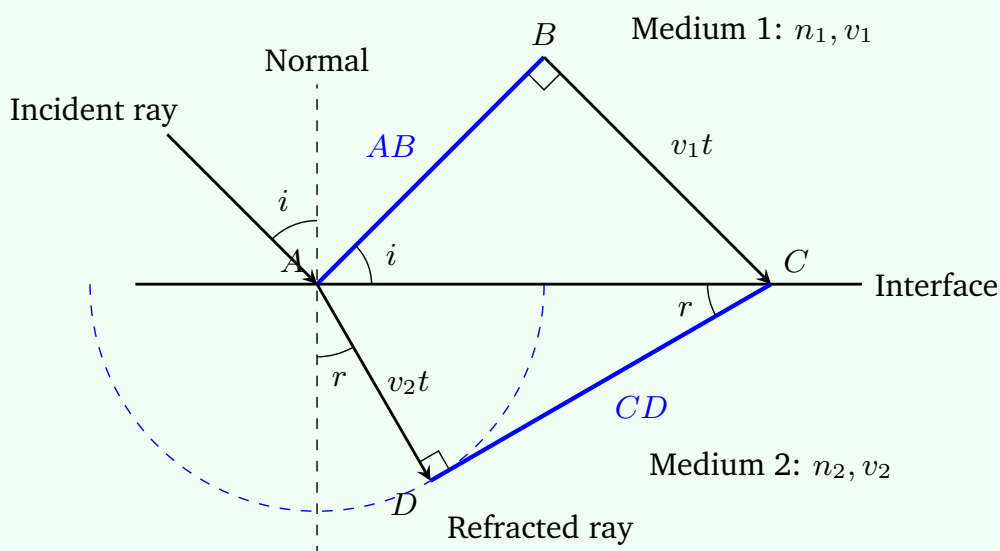
21(a). Using Huygens' principle, draw a ray diagram showing the propagation of a plane wave refracting at a plane surface separating two media. Also verify Snell's law of refraction. [2 marks]

Solution:

Concept:

- Huygens' principle states that each point of a wavefront emits secondary wavelets; their forward common tangent is the new wavefront.
- Rays are perpendicular to wavefronts. In medium j , light speed is $v_j = c/n_j$, where n_j is its refractive index.

Step 1: Construct the refracted wavefront Let the incident plane wavefront AB meet the interface first at A . In time t , the disturbance at B travels to C in medium 1, so $BC = v_1 t$. Meanwhile the secondary wavelet centred at A in medium 2 grows to radius $AD = v_2 t$. The tangent CD drawn from C to this wavelet is the refracted wavefront, with $AD \perp CD$. The sketch uses $v_2 < v_1$; the derivation applies generally.



Huygens construction: AB is incident, CD refracted; arrows show rays.

Step 2: Compare the two right triangles The angle between AB and the interface AC is the incidence angle i , since the incident ray and surface normal are respectively perpendicular to those lines. Similarly the angle between CD and AC is the refraction angle r . Thus

$$\sin i = \frac{BC}{AC} = \frac{v_1 t}{AC}, \quad \sin r = \frac{AD}{AC} = \frac{v_2 t}{AC}.$$

Dividing eliminates the common time and interface length:

$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \frac{c/n_1}{c/n_2} = \frac{n_2}{n_1}.$$

Step 3: Conclusion The Huygens construction gives $n_1 \sin i = n_2 \sin r$, which verifies Snell's law of refraction.

Quick Tip to Solve: Use the shared hypotenuse AC : the two sine ratios contain the distances travelled in the same time, so their ratio is v_1/v_2 .

OR

21(b). Why is a reflecting telescope preferred over a refracting telescope? Justify your answer giving two reasons. [2 marks]

Solution:

Concept:

- A reflecting telescope uses a concave mirror as its objective, whereas a refracting telescope uses a converging lens to collect light from distant objects.
- Reflection does not disperse light into different colours. The light-gathering power of an objective is proportional to its collecting area, and hence to the square of its diameter.

Step 1: Explain the absence of chromatic aberration The focal length of a mirror is independent of the wavelength of light, so different colours reflected by the objective have the same focus. A lens has

a wavelength-dependent refractive index and therefore different focal lengths for different colours. Thus the reflecting telescope avoids the coloured fringes and image blurring caused by chromatic aberration in a simple refracting telescope.

Step 2: Explain the advantage of a large aperture A mirror can be supported from its back, making a large objective easier to construct and support than a large lens, which must be supported at its rim. A larger mirror collects more light from faint celestial objects and gives better angular resolution. Consequently a reflecting telescope can provide brighter and more detailed views of distant objects with a practically achievable large aperture.

Step 3: Conclusion A reflecting telescope is preferred because its objective is free from chromatic aberration and can be made with a larger aperture, improving light collection and resolving power.

Quick Tip to Solve: Link each advantage to the mirror: wavelength-independent reflection removes colour error; and back support makes a large aperture practical.

22. Two coherent monochromatic light beams of intensities I and $4I$ superpose each other. Find the ratio of maximum and minimum intensities in the resulting beam. [2 marks]

Solution:

Concept:

- Coherent beams maintain a constant phase relationship and produce interference. For beams of the same polarization, the resultant intensity is $I_R = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \phi$, where ϕ is their phase difference.
- Intensity is proportional to the square of amplitude. Therefore the maximum and minimum intensities are $I_{\max} = (\sqrt{I_1} + \sqrt{I_2})^2$ and $I_{\min} = (\sqrt{I_1} - \sqrt{I_2})^2$.

Step 1: Find the amplitude ratio and maximum intensity The individual intensities are $I_1 = I$ and $I_2 = 4I$, so their amplitudes are in the ratio 1 : 2, not 1 : 4. At constructive interference the phase difference is an integral multiple of 2π , and amplitudes add:

$$I_{\max} = (\sqrt{I} + \sqrt{4I})^2 = (\sqrt{I} + 2\sqrt{I})^2 = 9I.$$

Step 2: Find the minimum intensity and form the ratio At destructive interference the phase difference is an odd multiple of π , so the amplitudes subtract. Since the amplitudes are unequal, cancellation is incomplete and the minimum is nonzero:

$$I_{\min} = (2\sqrt{I} - \sqrt{I})^2 = I, \quad \frac{I_{\max}}{I_{\min}} = \frac{9I}{I} = 9.$$

Step 3: Conclusion The ratio of maximum to minimum intensity is $I_{\max} : I_{\min} = 9 : 1$.

Quick Tip to Solve: Take square roots of the two intensities first; square their sum and difference to obtain the interference extrema.

23. The ground state energy of hydrogen atom is -13.6 eV. What is the potential energy and kinetic energy of an electron in the third excited state? [2 marks]

Solution:

Concept:

- In the Bohr model, the total energy of hydrogen in level n is $E_n = -13.6/n^2$ eV, with zero energy assigned to a separated electron and proton.
- For an electron bound by the Coulomb force, potential energy $U = -2K$, where K is kinetic energy. Thus $E = K + U = -K$, so $K = -E$ and $U = 2E$.

Step 1: Identify the third excited state and its total energy The ground state corresponds to $n = 1$; the first, second and third excited states correspond to $n = 2, 3, 4$, respectively. Hence the required principal quantum number is $n = 4$, not $n = 3$. Its total energy is

$$E_4 = \frac{-13.6}{4^2} \text{ eV} = \frac{-13.6}{16} \text{ eV} = -0.85 \text{ eV}.$$

Step 2: Calculate the potential and kinetic energies Applying the energy relations for the attractive Coulomb interaction gives

$$U_4 = 2E_4 = 2(-0.85) = -1.70 \text{ eV},$$

$$K_4 = -E_4 = -(-0.85) = +0.85 \text{ eV}.$$

The negative potential energy describes attraction, whereas kinetic energy must be positive. Their sum is $-1.70 + 0.85 = -0.85$ eV, consistent with the bound-state total energy.

Step 3: Conclusion In the third excited state, the electron has potential energy -1.70 eV and kinetic energy $+0.85$ eV.

Quick Tip to Solve: For the third excited state use $n = 4$; then obtain potential and kinetic energies from $U = 2E$ and $K = -E$.

24(a). Differentiate between intrinsic and extrinsic semiconductors. [2 marks]

Solution:

Concept:

- Electrical conduction in a semiconductor is due to mobile electrons and holes. A hole behaves as a positive charge carrier in the valence band.
- Doping means deliberately adding a small, controlled amount of a suitable impurity to a pure semiconductor to increase its charge-carrier concentration and conductivity.

Step 1: Compare composition and source of carriers An intrinsic semiconductor is a pure semiconductor, such as pure silicon or germanium, without intentional doping. Its free electrons and holes are generated thermally in pairs. An extrinsic semiconductor is obtained by doping the pure material with a suitable impurity. In silicon or germanium, a pentavalent donor produces an n-type material, while a trivalent acceptor produces a p-type material.

Step 2: Compare carrier concentrations and conductivity In an intrinsic semiconductor, the electron concentration n_e and hole concentration n_h are equal: $n_e = n_h = n_i$, where n_i is the intrinsic carrier concentration. In an extrinsic semiconductor in its usual operating range, the concentrations are unequal: electrons are majority carriers in n-type material ($n_e > n_h$), while holes are majority carriers

in p-type material ($n_h > n_e$). Doping usually makes the conductivity higher than that of the intrinsic material at the same temperature. Both types remain electrically neutral overall.

Step 3: Conclusion Intrinsic semiconductors are pure and have equal electron and hole concentrations; extrinsic semiconductors are doped and have a majority carrier population, giving greater conductivity in the normal operating range.

Quick Tip to Solve: Compare purity and carrier balance first: intrinsic means equal carrier concentrations; n-type and p-type identify the majority carrier after doping.

OR

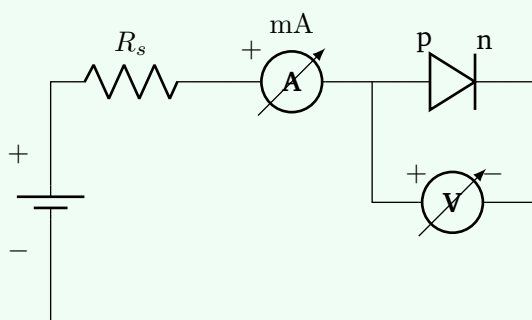
24(b). Draw the circuit arrangement for studying the V - I characteristics of a p-n junction diode in forward bias and reverse bias. Show the plot of V - I characteristic of a silicon diode. [2 marks]

Solution:

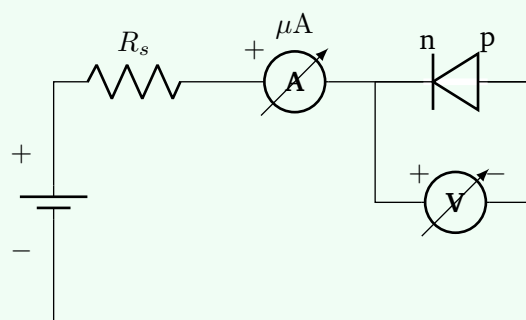
Concept:

- In forward bias the p side is connected to the positive terminal and the n side to the negative terminal; reverse bias interchanges these connections.
- An ammeter measures current in series, while a voltmeter measures the potential difference across the diode in parallel. Use a millimeter for forward current and a microammeter for reverse current.

Step 1: Connect the measuring circuits Use a variable DC supply and a series resistance R_s to limit current. In the forward circuit, the positive supply terminal feeds the p side of the silicon diode through the millimeter; in the reverse circuit it feeds the n side through the microammeter. The voltmeter is connected directly across the diode. Vary the supply and record successive pairs of diode voltage and current. The indicated meter polarities give positive readings in each circuit; assign negative voltage and current to the reverse-bias readings when plotting the combined graph.



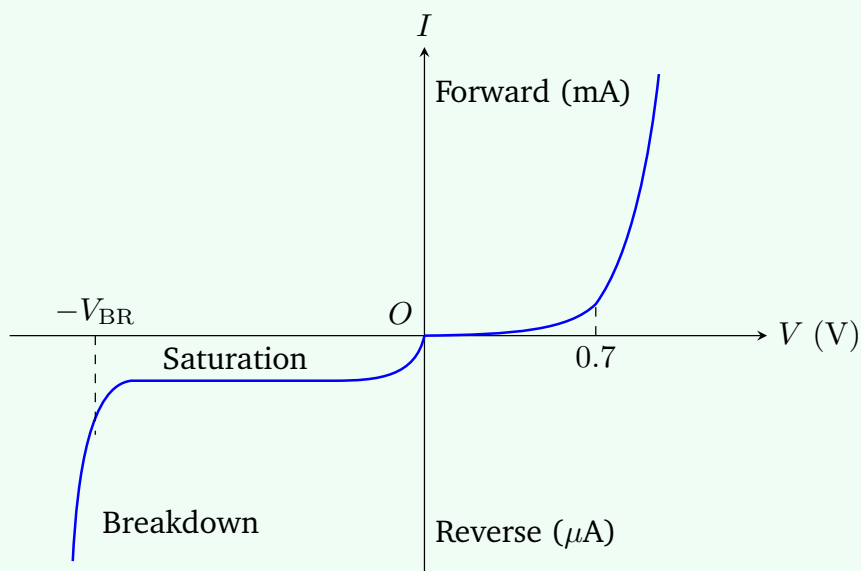
Forward bias



Reverse bias

Forward and reverse bias circuits; the supply voltage is variable.

Step 2: Plot the characteristic Plot diode current I vertically against diode voltage V horizontally. The forward current is initially very small and rises rapidly beyond a knee voltage of approximately 0.7 V for silicon. Under reverse bias a small, nearly constant reverse saturation current flows until breakdown, where its magnitude rises sharply. Forward current is measured in mA and reverse current in microamperes, so the two vertical scales are different in the schematic plot. Keep the reverse test voltage below breakdown during ordinary measurements.



Silicon diode characteristic (schematic; unequal current scales).

Step 3: Conclusion The circuits show the required series current measurement and parallel voltage measurement. Silicon exhibits a forward knee near 0.7 V and a small reverse saturation current before breakdown.

Quick Tip to Solve: Identify the diode's bar as the n side: positive supply to p gives forward bias; positive supply to n gives reverse bias.

25. Briefly explain how the diffusion and drift currents contribute to the formation of potential barrier in a p-n junction diode. [2 marks]

Solution:

Concept:

- Diffusion is the movement of carriers from a region of higher concentration to lower concentration. Drift is carrier motion caused by an electric field.
- The depletion region contains fixed negative acceptor ions on the p side and fixed positive donor ions on the n side. Their field creates the junction potential barrier.

Step 1: Follow diffusion and the formation of space charge Immediately after the junction is formed, electrons diffuse from the n side to the p side and holes diffuse from p to n because of their concentration gradients. Carriers recombine near the junction, leaving behind immobile ionised donors on n and acceptors on p. This region is depleted of mobile majority carriers. Its electric field is directed from n to p, and the resulting potential barrier opposes further majority-carrier diffusion. The conventional diffusion current is from p to n.

Step 2: Establish the opposing drift current The junction field drives minority electrons in p towards n and minority holes in n towards p. Both motions produce conventional drift current from n to p, opposite to the diffusion current. As the barrier grows, diffusion is reduced. At thermal equilibrium, with no external bias, the two currents have equal magnitudes and opposite directions:

$$I_{\text{diffusion}} + I_{\text{drift}} = 0.$$

Thus microscopic carrier motion continues even though the net current is zero; the depletion layer and built-in barrier remain present.

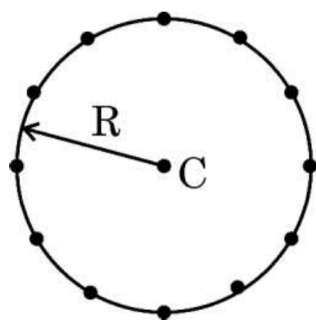
Step 3: Conclusion Diffusion and recombination create the depletion-layer space charge and potential barrier. Its electric field produces an opposing drift current; equilibrium is reached when drift and diffusion currents balance.

Quick Tip to Solve: Track conventional current separately from electron motion: diffusion current is p to n, while the built-in field and drift current are n to p.

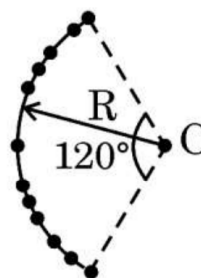
Section C (15 marks)

26. (a) Twelve negative charges of same magnitude are equally spaced and fixed on the circumference of a circle of radius R as shown in Fig. (i). Relative to potential being zero at infinity, find the electric potential and electric field at the centre C of the circle.

(b) If the charges are unequally spaced and fixed on an arc of 120° of radius R as shown in Fig. (ii), find electric potential at the centre C . [3 marks]



(i)



(ii)

Solution:

Concept:

- The potential due to a point charge Q , at distance r with zero at infinity, is $V = kQ/r$, where $k = 1/(4\pi\epsilon_0)$. Potentials add algebraically because potential is a scalar.
- Electric fields add as vectors. Equal charges at opposite ends of a diameter produce equal and opposite electric fields at the centre.

Step 1: Add the twelve potentials for the full circle Let each negative charge be $-q$, with $q > 0$. All twelve charges are at the same distance R from C . Consequently every contribution to the potential is negative and has the same value, irrespective of angular position:

$$V_C = \sum_{j=1}^{12} \frac{k(-q)}{R} = -\frac{12kq}{R}.$$

There is no cancellation of potential: the scalar contributions all have the same sign.

Step 2: Use diametrically opposite pairs for the field The angular separation is $360^\circ/12 = 30^\circ$. Hence

each charge has an equal charge diametrically opposite to it. The field at C due to either negative charge points towards that charge and has magnitude kq/R^2 . The two directions are opposite, so each pair has zero resultant field. There are six such pairs:

$$\vec{E}_C = \sum_{\text{six pairs}} (\vec{E}_j - \vec{E}_j) = \vec{0}.$$

A zero field at this point does not imply zero potential; field cancellation depends on directions, whereas potential does not.

Step 3: Recalculate the potential for the arc In part (b), the same twelve charges are unequally spaced on the 120° arc. Their angular positions change, but their distances from C remain R . Therefore the same scalar sum applies:

$$V_C = 12 \left(-\frac{kq}{R} \right) = -\frac{12kq}{R}.$$

No angular fraction is needed: the number of charges remains twelve. The electric field generally changes because the diametrically opposite pairs are absent, but part (b) asks only for potential.

Step 4: Conclusion For each charge $-q$, part (a) gives $V_C = -12q/(4\pi\epsilon_0 R)$ and $\vec{E}_C = \vec{0}$. Part (b) gives the same potential, $V_C = -12q/(4\pi\epsilon_0 R)$, despite the changed spacing.

Quick Tip to Solve: When every charge is at the same distance from the point, use $V = kQ_{\text{total}}/R$; inspect angular symmetry separately for the electric field.

27(a). How does the resistance differ from impedance? With the help of a suitable phasor diagram, obtain an expression for impedance of a series LCR circuit, connected to a source $v = v_m \sin \omega t$.

[3 marks]

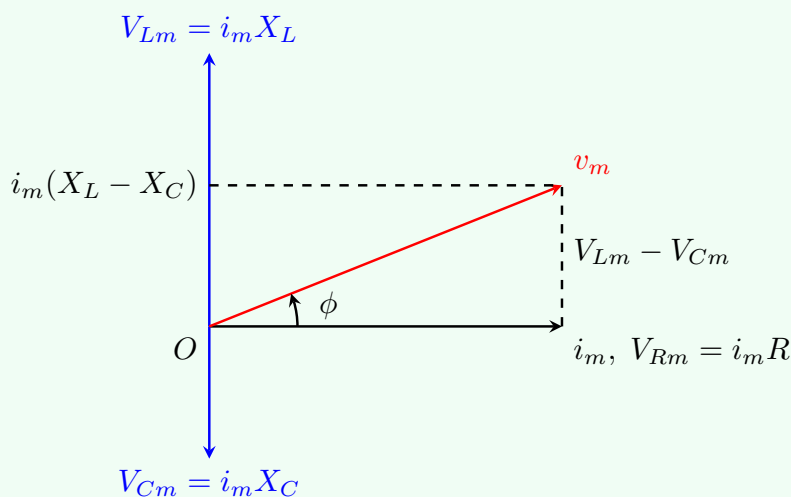
Solution:

Concept:

- Resistance R is the dissipative opposition to current. Impedance Z is the total opposition to alternating current, including resistance and reactance. Both are measured in Ω .
- For angular frequency ω , the inductive reactance is $X_L = \omega L$ and capacitive reactance is $X_C = 1/(\omega C)$. Voltage leads current by 90° in an ideal inductor and lags it by 90° in an ideal capacitor.

Step 1: Distinguish resistance from impedance Resistance represents conversion of electrical energy into heat. In an ideal resistor, voltage and current are in phase and R is independent of the AC frequency. Impedance also includes opposition caused by energy storage in the inductor and capacitor; thus it generally depends on frequency and can be associated with a phase difference between the supply voltage and current. For a purely resistive circuit, $Z = R$; in a general series LCR circuit, reactive contributions must also be included.

Step 2: Construct the voltage phasors using the common current Since the elements are in series, the same current of peak value i_m flows through all three. Take its phasor along the positive horizontal axis. The resistor voltage $V_{Rm} = i_m R$ lies on this axis. The inductor voltage $V_{Lm} = i_m X_L$ points upwards and the capacitor voltage $V_{Cm} = i_m X_C$ points downwards. These last two are opposite, so their resultant is $V_{Lm} - V_{Cm}$. The diagram illustrates the inductive case $X_L > X_C$; for the capacitive case the resultant lies below the horizontal axis.



Voltage phasors with current as reference; shown for $X_L > X_C$.

Step 3: Apply phasor addition and obtain the impedance The supply-voltage phasor is the vector sum of the three component phasors. The horizontal and vertical components form a right triangle:

$$\begin{aligned} v_m^2 &= V_{Rm}^2 + (V_{Lm} - V_{Cm})^2 \\ &= i_m^2 [R^2 + (X_L - X_C)^2]. \end{aligned}$$

By definition $Z = v_m/i_m$, hence

$$Z = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}.$$

The phase angle obeys $\tan \phi = (X_L - X_C)/R$. For the given source $v = v_m \sin \omega t$, the current is $i = (v_m/Z) \sin(\omega t - \phi)$; it lags for a positive ϕ and leads for a negative ϕ .

Step 4: Conclusion Resistance accounts for dissipative opposition alone, while the series LCR impedance is $Z = \sqrt{R^2 + (\omega L - 1/(\omega C))^2}$, including both resistance and net reactance.

Quick Tip to Solve: Subtract X_C from X_L first because their voltage phasors oppose each other; then combine the result with R using Pythagoras.

OR

27(b). Find the condition for resonance in a series LCR circuit connected to a source $v = v_m \sin \omega t$, where ω can be varied. Give the factors on which the resonant frequency of a series LCR circuit depends. Plot a graph showing the variation of electric current with frequency in a series LCR circuit. [3 marks]

Solution:

Concept:

- In a series LCR circuit, the inductive and capacitive reactances are $X_L = \omega L$ and $X_C = 1/(\omega C)$. Here L , C and R are the inductance, capacitance and resistance.
- For a fixed source-voltage amplitude v_m , the current amplitude is $I_m = v_m/Z$, where $Z = \sqrt{R^2 + (X_L - X_C)^2}$. Resonance occurs when this current is maximum.

Step 1: Minimise the impedance As the angular frequency changes, the resistance stays fixed while the net reactance changes. The smallest possible impedance is obtained when its non-negative reactance term vanishes:

$$\omega_0 L - \frac{1}{\omega_0 C} = 0 \Rightarrow \omega_0^2 LC = 1.$$

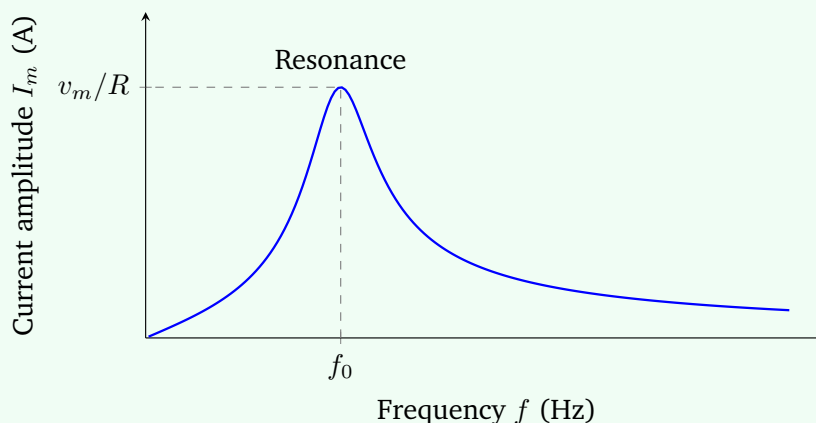
Thus the condition is $X_L = X_C$. The inductive and capacitive voltage phasors cancel; the applied voltage and current are then in phase. The impedance is R , so the resonant current amplitude is v_m/R .

Step 2: Identify the factors controlling resonance Using $\omega_0 = 2\pi f_0$, the ordinary resonant frequency is

$$f_0 = \frac{1}{2\pi\sqrt{LC}}.$$

It depends on the inductance and capacitance, varying inversely as the square root of either when the other is held fixed. For this ideal series circuit, R changes the height and width of the current peak but does not change f_0 .

Step 3: Sketch the resonance curve For a fixed voltage amplitude, plot current amplitude against frequency. At very low frequency the capacitor offers large reactance; at very high frequency the inductor does so. Therefore the current is small at either extreme and reaches its maximum at f_0 . The curve below shows the peak explicitly; the same shape applies to rms current if rms source voltage is used.



Current amplitude versus frequency at fixed source-voltage amplitude.

Step 4: Conclusion Resonance requires $\omega_0 L = 1/(\omega_0 C)$, giving $\omega_0 = 1/\sqrt{LC}$ and $f_0 = 1/(2\pi\sqrt{LC})$. Only L and C determine the resonant frequency; the peak current is $I_{m,\max} = v_m/R$.

Quick Tip to Solve: Set the two reactances equal first; use the factor 2π only when converting angular frequency to frequency in hertz.

28. A long solenoid of radius r consists of n turns per unit length. A current $I = I_0 \sin \omega t$ flows in the solenoid. A coil of N turns is wound tightly around it near its centre. What is:

(a) the induced emf in the coil?

(b) the mutual inductance between the solenoid and the coil?

[3 marks]

Solution:

Concept:

- The magnetic field near the centre of a long air-core solenoid is $B = \mu_0 n I$, where n is the number of turns per unit length and μ_0 is the permeability of free space.
- Faraday's law gives the induced emf as $\varepsilon = -d(N\Phi)/dt$, where Φ is the flux through one turn of the surrounding coil. Mutual inductance is defined by the flux linkage $N\Phi = MI$.

Step 1: Calculate the flux linked with the coil The coil is wound tightly around the solenoid, so its effective area is the solenoid cross-section $A = \pi r^2$. Near the centre, the magnetic field is approximately uniform and perpendicular to this area. Taking the positive area normal along the field produced by positive solenoid current,

$$\Phi = BA = \mu_0 n I \pi r^2.$$

With N turns and $I = I_0 \sin \omega t$, the total flux linkage is

$$N\Phi = \mu_0 n N \pi r^2 I_0 \sin \omega t.$$

Step 2: Find the induced emf for part (a) Differentiate the flux linkage with respect to time. The geometrical factors and the current amplitude are constants, while $d(\sin \omega t)/dt = \omega \cos \omega t$. Hence

$$\varepsilon(t) = -\mu_0 n N \pi r^2 I_0 \omega \cos \omega t.$$

Its peak magnitude is $\varepsilon_0 = \mu_0 n N \pi r^2 I_0 \omega$. The negative sign expresses Lenz's law: the induced emf drives a current whose field opposes the change of linked flux. Reversing the coil's chosen terminal polarity reverses the reported emf sign.

Step 3: Identify the mutual inductance for part (b) Compare $N\Phi = \mu_0 n N \pi r^2 I$ with the definition $N\Phi = MI$. Thus

$$M = \mu_0 n N \pi r^2.$$

This is also consistent with $\varepsilon = -M dI/dt$. The unit of M is henry, since μ_0 has unit H m^{-1} , n has unit m^{-1} , and r^2 has unit m^2 . In the stated geometry, M depends on the dimensions and turn densities, not on the instantaneous current.

Step 4: Conclusion (a) The induced emf is $\varepsilon(t) = -\mu_0 n N \pi r^2 I_0 \omega \cos \omega t$, with polarity defined by the chosen positive flux normal. (b) The mutual inductance is $M = \mu_0 n N \pi r^2$, in henry.

Quick Tip to Solve: Use n in the solenoid field and N in the outer coil's flux linkage; differentiate the sinusoidal current only after multiplying by the linked area.

- 29. How does Einstein's photoelectric equation explain the emission of electrons from a metal surface? Explain briefly. Plot the variation of photocurrent with:**
- (a) collector plate potential for different intensity of incident radiation, and
- (b) intensity of incident radiation.

[3 marks]

Solution:

Concept:

- In Einstein's photon picture, an electron absorbs the energy $h\nu$ of one photon. Here h is Planck's constant and ν is the incident frequency. The work function ϕ is the minimum energy needed to escape from the metal.
- Energy conservation gives $K_{\max} = h\nu - \phi = h(\nu - \nu_0)$, where $\nu_0 = \phi/h$ is the threshold frequency. Photocurrent measures the rate at which emitted electrons reach the collector.

Step 1: Explain the emission of electrons The absorbed photon supplies the escape energy ϕ ; the remainder appears as the maximum kinetic energy of a photoelectron:

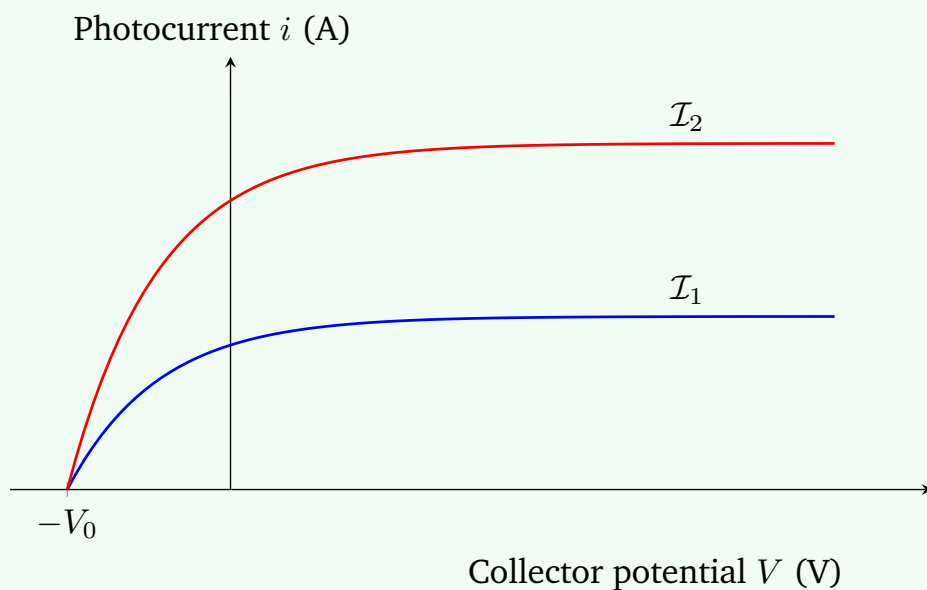
$$h\nu = \phi + K_{\max} = \phi + \frac{1}{2}m_e v_{\max}^2.$$

If $\nu < \nu_0$, one photon has insufficient energy to release an electron, irrespective of intensity. For $\nu > \nu_0$, emission can occur without a measurable time lag because the energy arrives in one photon interaction. Increasing intensity at fixed frequency increases the photon arrival rate and hence the number of photoelectrons, while $K_{\max}$ remains unchanged.

Step 2: Plot current against collector potential for part (a) Keep the frequency fixed above threshold and use two intensities $\mathcal{I}_2 > \mathcal{I}_1$. A positive collector potential attracts electrons; as it increases, the current reaches saturation when all emitted electrons are collected. Higher intensity gives a larger saturation current. A negative collector potential retards the electrons. Both curves reach zero at the same stopping potential $-V_0$, because

$$eV_0 = K_{\max} = h\nu - \phi$$

depends on frequency and the metal, not on intensity. At zero collector potential some electrons still reach the collector because of their initial kinetic energy.

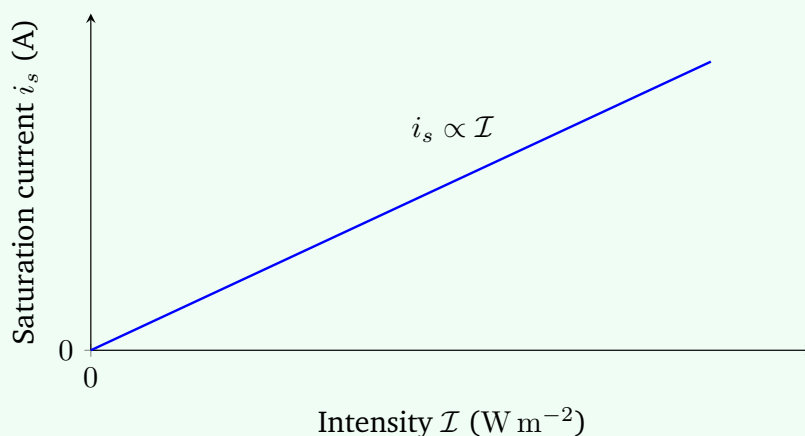


(a) Photocurrent versus collector potential at the same frequency, with $I_2 > I_1$.

Step 3: Plot current against intensity for part (b) Keep frequency, illuminated area and collector potential fixed. In particular, use a sufficiently positive collector potential to measure the saturation current. The photon arrival rate is proportional to intensity; hence the number of emitted and collected electrons per second is proportional to intensity:

$$i_s = e \frac{\text{number of collected electrons}}{\text{time}} \Rightarrow i_s \propto \mathcal{I}.$$

The graph is a straight line through the origin under these conditions, neglecting background current.



(b) Saturation photocurrent versus incident intensity at fixed frequency and collecting potential.

Step 4: Conclusion Einstein's equation $h\nu = \phi + K_{\text{max}}$ explains the threshold and the electron's escape energy. At fixed frequency, higher intensity increases saturation current but leaves stopping potential unchanged. Photocurrent is proportional to incident intensity at a fixed collecting potential.

Quick Tip to Solve: For different intensities at the same frequency, draw different saturation levels but one common negative stopping potential; intensity changes electron numbers, not maximum energy.

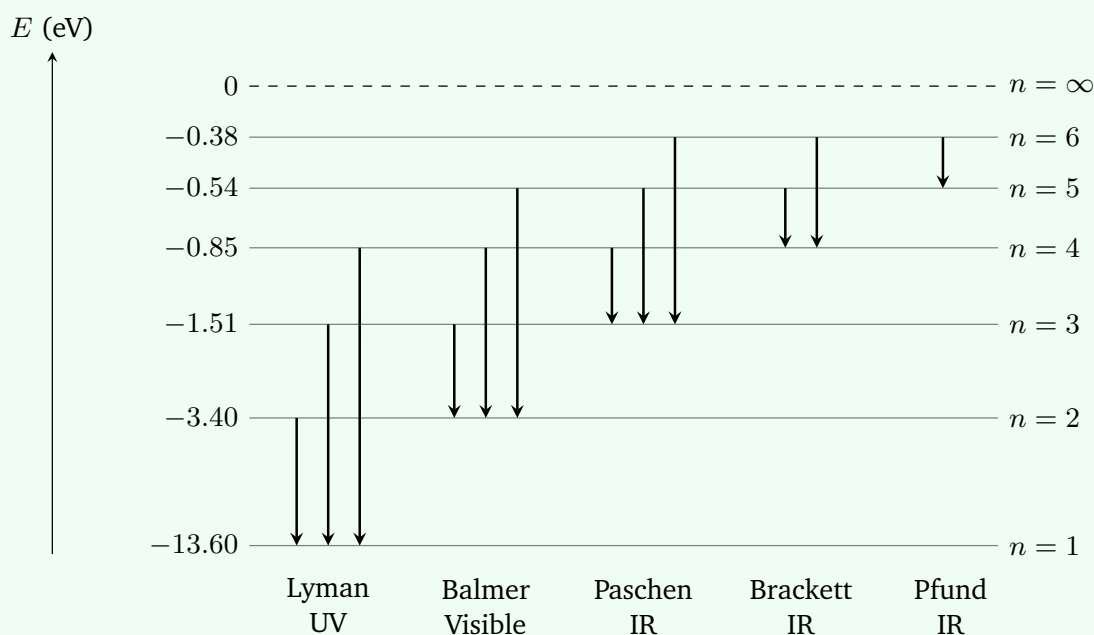
30(a). Draw the energy level diagram for hydrogen atom. Mark the transitions corresponding to the series lying in the ultraviolet region, visible region and infrared region. [3 marks]

Solution:

Concept:

- Hydrogen has discrete bound-state energies $E_n = -13.6/n^2$ eV, where $n = 1, 2, 3, \dots$ is the principal quantum number; $E = 0$ is the ionisation limit.
- A downward transition emits a photon of energy $h\nu = E_i - E_f$. A spectral series consists of transitions from different higher levels to the same final level n_f .

Step 1: Draw and label the allowed energy levels Put energy on the vertical axis, increasing upwards. The lowest level is the ground state $n = 1$ at -13.6 eV. The next levels are $n = 2$ at -3.40 eV, $n = 3$ at -1.51 eV, $n = 4$ at -0.85 eV and $n = 5$ at -0.54 eV. The separation decreases as n increases, and the levels approach zero energy. The diagram uses expanded upper-level spacing so that the transitions remain readable.



Hydrogen energy levels and representative emission transitions (vertical spacing schematic).

Step 2: Group the emission transitions by their final level **Ultraviolet:** the Lyman series has $n_i = 2, 3, 4, \dots \rightarrow n_f = 1$. **Visible:** the Balmer series has $n_i = 3, 4, 5, \dots \rightarrow n_f = 2$; its prominent lines are visible, while the high-order lines approach a near-ultraviolet limit. **Infrared:** the Paschen series has $n_i = 4, 5, 6, \dots \rightarrow n_f = 3$. Brackett transitions end at $n_f = 4$, and Pfund transitions end at $n_f = 5$; these series are also infrared. Each downward arrow in the diagram represents photon emission, not absorption.

Step 3: Conclusion Transitions ending at $n = 1$ form the ultraviolet Lyman series; those ending at $n = 2$ form the conventionally visible Balmer series. Transitions ending at $n = 3, 4, 5$ give the infrared Paschen, Brackett and Pfund series respectively.

Quick Tip to Solve: Identify a series from the arrow's lower endpoint: final levels 1, 2 and 3 mean Lyman, Balmer and Paschen respectively.

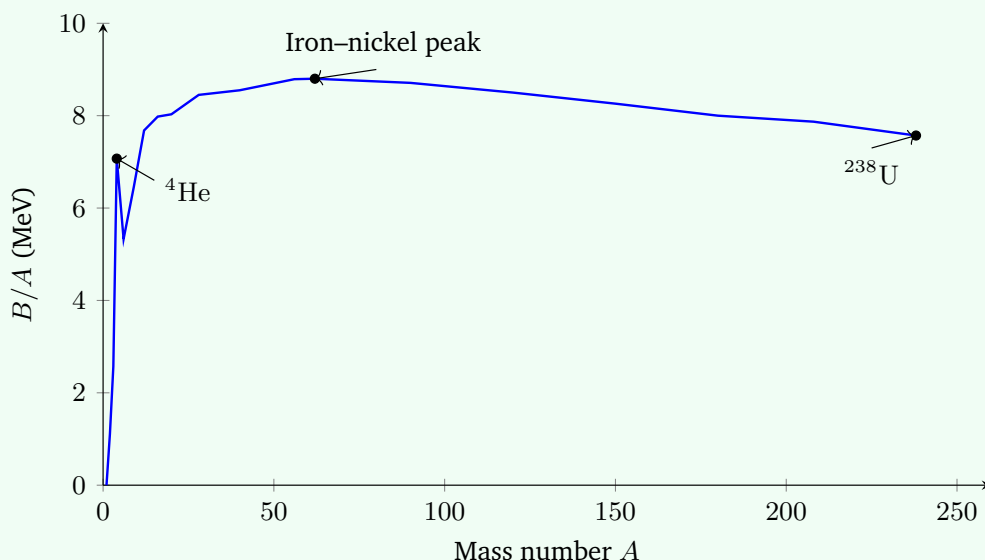
30(b). Draw a diagram to show the variation of binding energy per nucleon with mass number for different nuclei and mention its two features. Why do lighter nuclei usually undergo nuclear fusion? [3 marks]

Solution:

Concept:

- Binding energy B is the energy required to separate a nucleus into its free nucleons. The binding energy per nucleon is B/A , where A is the mass number.
- A larger B/A generally indicates a more tightly bound nucleus. A nuclear reaction releases energy when the total binding energy of its products exceeds that of its reactants.

Step 1: Sketch the variation of binding energy per nucleon Draw mass number A along the horizontal axis and B/A in MeV along the vertical axis. For hydrogen, $A = 1$ and the nuclear binding energy is zero. For light nuclei the curve rises rapidly, with local irregularities such as the strongly bound helium nucleus. It reaches a broad maximum near the iron-nickel region, then falls slowly towards the heaviest nuclei. The plotted curve represents this overall trend.



Schematic binding-energy-per-nucleon curve; the peak lies in the iron-nickel region.

Step 2: State two features of the curve **First feature:** binding energy per nucleon increases rapidly for light nuclei and has its maximum of about 8.8 MeV near $A \approx 56$ to 62. Nuclei in the iron-nickel region are therefore among the most tightly bound. **Second feature:** for medium-mass nuclei, approximately $30 < A < 170$, it remains nearly constant at about 8 MeV, followed by a gradual decrease to about 7.6 MeV for uranium. The nearly constant middle region reflects the short range and saturation of nuclear forces.

Step 3: Explain why fusion of light nuclei releases energy When suitable light nuclei combine to form a heavier nucleus nearer the peak, the products have greater binding energy per nucleon. For the conserved total number of nucleons, the total binding energy consequently increases. The product rest mass is smaller, and the mass difference appears as released energy:

$$Q = B_{\text{products}} - B_{\text{reactants}} = (m_{\text{reactants}} - m_{\text{products}})c^2 > 0.$$

Thus fusion is energetically favourable for suitable light nuclei. It requires sufficiently high temperature

or another means of overcoming their electrostatic repulsion; the curve does not imply that fusion occurs spontaneously under ordinary conditions.

Step 4: Conclusion The curve rises steeply for light nuclei, has a broad maximum near $A \approx 56$ to 62, and falls gradually for heavy nuclei. Fusion of suitable light nuclei releases energy by forming more tightly bound products with a greater binding energy per nucleon.

Quick Tip to Solve: To predict energy release, compare the products with the reactants on the curve: moving towards the iron-nickel peak increases binding energy per nucleon.

Section D (15 marks)

31(a). (i) State Coulomb's law in electrostatics and write it in vector form, for two charges.

(ii) 'Gauss's law is based on the inverse-square dependence on distance contained in the Coulomb's law.' Explain.

(iii) Two charges A (charge q) and B (charge $2q$) are located at points $(0, 0)$ and (a, a) respectively. Let $\hat{i}$ and $\hat{j}$ be the unit vectors along x -axis and y -axis respectively. Find the force exerted by A on B , in terms of $\hat{i}$ and $\hat{j}$. [5 marks]

Solution:

Concept:

- Coulomb's law gives the electrostatic force between two stationary point charges. In vacuum, $k = 1/(4\pi\epsilon_0)$, where ϵ_0 is the permittivity of free space.
- Electric flux through a surface is $\Phi = \oint \vec{E} \cdot d\vec{S}$. Gauss's law states $\oint \vec{E} \cdot d\vec{S} = Q_{\text{enclosed}}/\epsilon_0$.
- A vector force requires both its magnitude and the unit vector from the source charge to the charge experiencing the force.

Step 1: (i) State Coulomb's law and specify the force vector The magnitude of the electrostatic force between two stationary point charges is directly proportional to the product of their charge magnitudes and inversely proportional to the square of their separation. The force acts along the line joining them; like charges repel and unlike charges attract.

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

Let $\vec{r}_1$ and $\vec{r}_2$ be the position vectors of the charges, and let $\hat{r}_{12}$ point from charge 1 to charge 2. The force on charge 2 due to charge 1 is

$$\vec{F}_{2 \leftarrow 1} = k \frac{q_1 q_2}{r^2} \hat{r}_{12} = k q_1 q_2 \frac{\vec{r}_2 - \vec{r}_1}{|\vec{r}_2 - \vec{r}_1|^3}.$$

The signed product $q_1 q_2$ automatically reverses the direction for unlike charges. The force on charge 1 is equal and opposite.

Step 2: (ii) Relate the inverse-square field to Gauss's law Surround a point charge Q by a sphere of radius r . Its field is radial, has the same magnitude everywhere on the sphere, and is parallel to the outward area vector for positive Q . Using the signed radial component,

$$\Phi = \frac{kQ}{r^2} (4\pi r^2) = 4\pi kQ = \frac{Q}{\epsilon_0}.$$

The r^2 from the surface area cancels the r^{-2} in Coulomb's field, making the flux independent of the sphere's radius. A different distance dependence would not give this cancellation. For a general surface element, $d\Phi = kQ dS \cos \theta / r^2 = kQ d\Omega$, where $d\Omega$ is its signed solid angle at the charge. A closed surface enclosing the charge subtends 4π ; a charge outside contributes zero net solid angle. Adding the contributions of all charges gives $\Phi = Q_{\text{enclosed}}/\epsilon_0$ for any closed surface.

Step 3: (iii) Find the separation and force components From $A(0, 0)$ to $B(a, a)$, for the positive length a ,

$$\vec{r}_{AB} = a\hat{i} + a\hat{j}, \quad r_{AB} = \sqrt{2}a, \quad \hat{r}_{AB} = \frac{\hat{i} + \hat{j}}{\sqrt{2}}.$$

The charge product is $q(2q) = 2q^2$, so the force is repulsive. Substitute the separation and the unit vector into Coulomb's law:

$$\begin{aligned} \vec{F}_{B \leftarrow A} &= k \frac{2q^2}{(\sqrt{2}a)^2} \frac{\hat{i} + \hat{j}}{\sqrt{2}} \\ &= \frac{kq^2}{\sqrt{2}a^2} (\hat{i} + \hat{j}). \end{aligned}$$

Both components are positive and equal. Its magnitude is kq^2/a^2 , consistent with the scalar law.

Step 4: Conclusion Coulomb's vector law is $\vec{F}_{2 \leftarrow 1} = kq_1q_2\hat{r}_{12}/r^2$. Its inverse-square dependence yields the distance-independent closed-surface flux $Q_{\text{enclosed}}/\epsilon_0$. For the given charges,

$$\boxed{\vec{F}_{B \leftarrow A} = \frac{q^2}{4\pi\epsilon_0\sqrt{2}a^2} (\hat{i} + \hat{j})}.$$

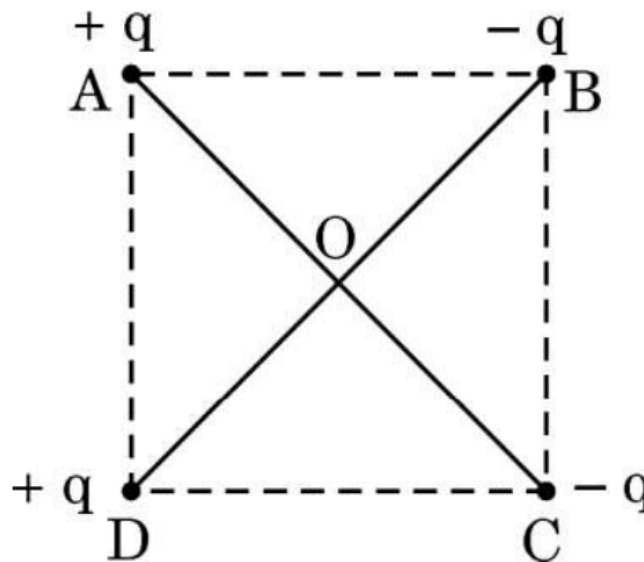
The force points from A towards B , at 45° to the positive x -axis; its SI unit is newton.

Quick Tip to Solve: First calculate the diagonal distance $\sqrt{2}a$, then multiply the force magnitude by $(\hat{i} + \hat{j})/\sqrt{2}$. The displacement itself is not a unit vector.

31(b). (i) Derive an expression for the electric field at a point on the equatorial plane of an electric dipole consisting of charges q and $-q$ separated by a distance $2a$.

(ii) The distance of a far off point on the equatorial plane of an electric dipole is halved. How will the electric field be affected for the dipole?

(iii) Two identical electric dipoles are placed along the diagonals of a square $ABCD$ of side $\sqrt{2}$ m as shown in the figure. Obtain the magnitude and direction of the net electric field at the centre (O) of the square. [5 marks]



Solution:

Concept:

- The electric dipole moment is $\vec{p} = q(2a)\hat{p}$, directed from $-q$ to $+q$; $2a$ is the charge separation and $\hat{p}$ is the unit vector along the dipole moment.
- Superposition gives the total electric field as the vector sum of the fields of individual charges. A positive charge produces an outward field and a negative charge an inward field.
- For a short dipole at a distant equatorial point, $\vec{E} = -k\vec{p}/r^3$, with $k = 1/(4\pi\epsilon_0)$ and r measured from the midpoint. This approximation requires $r \gg a$.

Step 1: (i) Resolve the two charge fields on the equatorial plane Place $-q$ at $(-a, 0)$, $+q$ at $(a, 0)$, and choose the equatorial point $P(0, r)$. By rotational symmetry about the dipole axis, this describes any point of the equatorial plane at distance r from the midpoint. Each charge is a distance $R = \sqrt{r^2 + a^2}$ from P . The field of $+q$ points along $-a\hat{i} + r\hat{j}$; the field of $-q$ points from P towards $-q$. Hence

$$\vec{E}_+ = \frac{kq}{(r^2 + a^2)^{3/2}}(-a\hat{i} + r\hat{j}),$$

$$\vec{E}_- = \frac{kq}{(r^2 + a^2)^{3/2}}(-a\hat{i} - r\hat{j}).$$

The components perpendicular to the dipole axis cancel, while the components opposite to $\vec{p}$ add. Therefore

$$\vec{E}_{eq} = -\frac{2kqa}{(r^2 + a^2)^{3/2}}\hat{i} = -\frac{k\vec{p}}{(r^2 + a^2)^{3/2}}.$$

Its magnitude is $kp/(r^2 + a^2)^{3/2}$, and its direction is opposite to the dipole moment. For $r \gg a$,

neglecting a^2 gives $\vec{E}_{\text{eq}} \simeq -k\vec{p}/r^3$.

Step 2: (ii) Apply the far-field distance dependence For a fixed dipole, the equatorial field magnitude varies as r^{-3} at a far-off point. If the new distance $r/2$ is also large compared with a ,

$$\frac{E'}{E} = \frac{kp/(r/2)^3}{kp/r^3} = 8.$$

Thus the field becomes eight times its previous magnitude. Its direction remains opposite to $\vec{p}$; halving the distance does not reverse the field.

Step 3: (iii) Use the actual corner charges at the square's centre In the given figure, A, D carry $+q$, while B, C carry $-q$. The square has side $s = \sqrt{2}$ m, so its diagonal is $s\sqrt{2} = 2$ m. Each corner is therefore $R_0 = 1$ m from the centre O . The field magnitude at O due to each charge is $E_0 = kq/R_0^2$. The two fields due to the charges on diagonal AC both point from A towards C , giving $2E_0$ along that diagonal. Similarly, the pair on DB gives $2E_0$ from D towards B . These two resultant fields are perpendicular. Equivalently, all four horizontal components point towards the negative-charge side BC ; their vertical components cancel. Taking $\hat{x}$ parallel to AB from left to right,

$$\vec{E}_{\text{net}} = 4E_0 \cos 45^\circ \hat{x} = \frac{2\sqrt{2}kq}{R_0^2} \hat{x}.$$

Here the observation point lies between each dipole's two charges. The far-field equatorial formula from part (i) must not be used for this geometry; summing the four point-charge fields gives the exact result.

Step 4: Conclusion (i) $\vec{E}_{\text{eq}} = -\frac{\vec{p}}{4\pi\epsilon_0(r^2 + a^2)^{3/2}}$, approaching $-\vec{p}/(4\pi\epsilon_0 r^3)$ far away. (ii) Halving the far-field distance increases the field eightfold. (iii) At the square's centre,

$$E_{\text{net}} = \frac{2\sqrt{2}}{4\pi\epsilon_0} \frac{q}{(1 \text{ m})^2}.$$

The direction is parallel to AB (or DC), from the positive-charge side AD towards the negative-charge side BC . For q in coulombs, this is $18\sqrt{2} \times 10^9 (q/\text{C}) \text{ N C}^{-1}$.

Quick Tip to Solve: At the square's centre, draw each charge's field direction mentally: all horizontal components add and the vertical ones cancel. Use corner-to-centre distance, half the diagonal.

- 32(a).** (i) State Biot-Savart's law for the magnetic field due to a current carrying element. Use this law to obtain an expression for the magnetic field at the centre of a circular loop of radius a and carrying a current I . Draw the magnetic field lines for a current loop indicating the direction of magnetic field. (ii) An electron is revolving around the nucleus in a circular orbit with a speed of 10^7 m s^{-1} . If the radius of the orbit is 10^{-10} m , find the current constituted by the revolving electron in the orbit.

[5 marks]

Solution:

Concept:

- Biot-Savart's law gives the field of a current element: $d\vec{B} = (\mu_0/4\pi)I d\vec{\ell} \times \hat{r}/r^2$. Here $d\vec{\ell}$ points along conventional current and $\hat{r}$ points from the element to the observation point.

- Fields add vectorially. For a circular loop, all elements produce a field in the same direction at its centre; the right-hand thumb rule fixes that direction.
- Current is charge crossing a reference point per unit time. A charge of magnitude e completing one revolution in period T gives $I = e/T$, with $T = 2\pi r/v$.

Step 1: (i) State Biot-Savart's law The magnetic field due to a short current element is directly proportional to its current I , its length $d\ell$, and $\sin \theta$, and inversely proportional to the square of its distance r from the observation point:

$$dB = \frac{\mu_0}{4\pi} \frac{I d\ell \sin \theta}{r^2}.$$

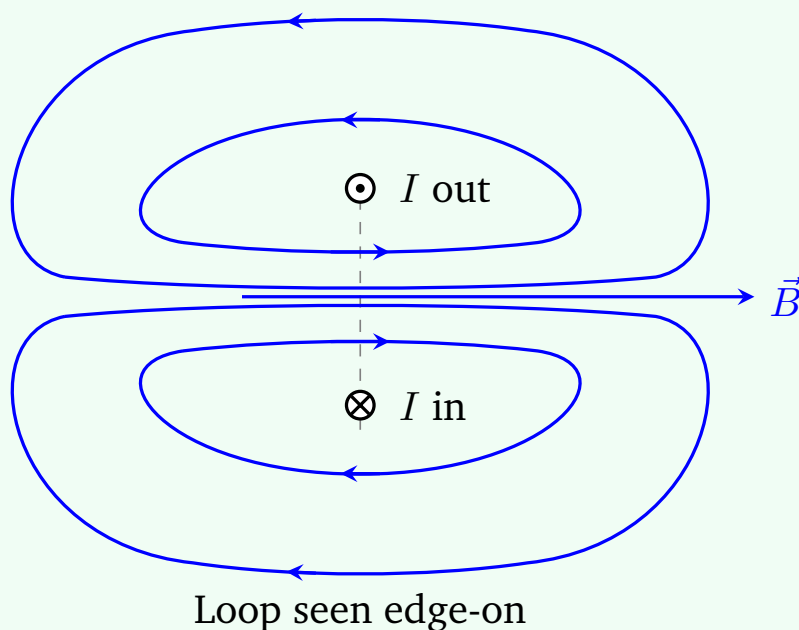
Here θ is the angle between $d\vec{\ell}$ and $\vec{r}$, and μ_0 is the permeability of free space. The direction of $d\vec{B}$ is perpendicular to the plane containing these vectors, along $d\vec{\ell} \times \hat{r}$.

Step 2: Sum the contributions at the centre Consider a circular loop of radius a . For every element, the distance from the centre is a , and the tangent $d\vec{\ell}$ is perpendicular to the inward radius vector. Thus $\theta = 90^\circ$ and $\sin \theta = 1$. All contributions point along the same normal to the loop, so their magnitudes can be added:

$$\begin{aligned} B &= \oint dB = \frac{\mu_0 I}{4\pi a^2} \oint d\ell, \\ \oint d\ell &= 2\pi a, \\ B &= \frac{\mu_0 I}{4\pi a^2} (2\pi a) = \frac{\mu_0 I}{2a}. \end{aligned}$$

Curl the fingers of the right hand along the current; the thumb gives the direction of the field through the centre. An anticlockwise current viewed face-on gives a field towards the observer; a clockwise current gives a field away.

Step 3: Draw and interpret the magnetic field lines The figure is a section through the axis of the loop, with the loop seen edge-on. The upper dot shows current out of the page and the lower cross shows current into it. The central field points to the right. Field lines pass through the interior in this direction and curve back outside to form closed loops. They are nearly straight and parallel close to the centre and spread out farther away. Reversing the current reverses every field arrow.



Magnetic field lines in an axial section of a current loop; dots and crosses specify the current direction.

Step 4: (ii) Find the period and the equivalent current In one revolution the electron travels the circumference $2\pi r$. Therefore, for $r = 10^{-10}$ m and $v = 10^7$ m s $^{-1}$,

$$T = \frac{2\pi r}{v} = \frac{2\pi \times 10^{-10}}{10^7} = 2\pi \times 10^{-17} \text{ s.}$$

One electron passes a chosen point on its orbit in each period. Using $e = 1.6 \times 10^{-19}$ C, the current magnitude is

$$\begin{aligned} I &= \frac{e}{T} = \frac{ev}{2\pi r} \\ &= \frac{1.6 \times 10^{-19} \times 10^7}{2\pi \times 10^{-10}} \\ &\simeq 2.55 \times 10^{-3} \text{ A.} \end{aligned}$$

Since the electron is negatively charged, the direction of conventional current is opposite to its direction of revolution. The orbital direction itself is not specified, so only this relative direction can be stated.

Step 5: Conclusion (i) The field at the centre of the circular loop is $B = \mu_0 I / (2a)$, normal to the loop in the right-hand-rule direction. (ii) The revolving electron constitutes a current of magnitude 2.55×10^{-3} A = 2.55 mA, opposite to the electron's motion.

Quick Tip to Solve: At a loop's centre, every element has the same distance and a right angle to the radius, so replace the integral of length by the circumference. For an orbiting electron, use one elementary charge per orbital period, not charge multiplied by the period.

32(b). (i) Derive an expression for the force acting on a current carrying straight conductor kept in a magnetic field. State the rule which is used to find the direction of this force. Give the condition under which this force is (1) maximum, and (2) minimum.

(ii) Two long parallel straight wires A and B are 2.5 cm apart in air. They carry 5.0 A and 2.5 A currents respectively in opposite directions. Calculate the magnitude of the force exerted by wire A on a 10 cm length of wire B . [5 marks]

Solution:

Concept:

- A moving charge experiences magnetic force $\vec{f} = q\vec{v} \times \vec{B}$. Forces on the drifting charge carriers add to give the force on a current-carrying conductor.
- For carrier number density n , cross-sectional area A , carrier charge magnitude e and drift speed v_d , the current magnitude is $I = neAv_d$.
- The field at distance r from a long straight wire carrying current I_A is $B_A = \mu_0 I_A / (2\pi r)$, where $\mu_0 = 4\pi \times 10^{-7}\text{ N A}^{-2}$ in air.

Step 1: (i) Derive the force on the conductor Consider a straight length l of uniform conductor wholly inside a uniform magnetic field $\vec{B}$. Its volume is Al , so it contains $N = nAl$ mobile electrons. The random thermal velocities average to zero, leaving the drift contribution. For electron drift velocity $\vec{v}_e$, summing the magnetic forces gives

$$\vec{F} = N(-e)\vec{v}_e \times \vec{B}.$$

Let $\hat{l}$ point along conventional current. Electrons drift oppositely, so $\vec{v}_e = -v_d \hat{l}$. The force transferred to the conductor is therefore

$$\begin{aligned}\vec{F} &= nAlev_d \hat{l} \times \vec{B} \\ &= Il \hat{l} \times \vec{B} = I\vec{l} \times \vec{B}.\end{aligned}$$

Here $\vec{l} = l\hat{l}$. If θ is the angle between conventional current and magnetic field, the magnitude is $F = BIl \sin \theta$.

Step 2: State the direction rule and limiting conditions Use Fleming's left-hand rule: hold the thumb, forefinger and middle finger of the left hand mutually perpendicular. The forefinger points along the magnetic field, the middle finger along conventional current, and the thumb along the force on the conductor. Thus the force is perpendicular to both current and field.

(1) For a fixed B , I and l , the force is maximum when $\theta = 90^\circ$, giving $F_{\max} = BIl$.

(2) It is minimum, equal to zero, when $\theta = 0^\circ$ or 180° : the conductor is parallel or antiparallel to the field.

Step 3: (ii) Find the field of wire A at wire B Convert the separation and length to SI units:

$$r = 2.5 \times 10^{-2}\text{ m}, \quad l_B = 10 \times 10^{-2}\text{ m} = 0.10\text{ m}.$$

With $I_A = 5.0\text{ A}$, the field at wire B is

$$B_A = \frac{(4\pi \times 10^{-7})(5.0)}{2\pi(2.5 \times 10^{-2})} = 4.0 \times 10^{-5}\text{ T}.$$

This field is perpendicular to wire B, so the sine factor in the force expression is unity.

Step 4: Calculate the force on the specified length of B Using $I_B = 2.5 \text{ A}$,

$$F_{A \rightarrow B} = B_A I_B l_B = (4.0 \times 10^{-5})(2.5)(0.10) = 1.0 \times 10^{-5} \text{ N}.$$

Opposite currents in parallel wires repel. Thus wire B is pushed away from wire A; the force calculated is on the stated length, rather than force per unit length.

Step 5: Conclusion (i) $\vec{F} = I\vec{l} \times \vec{B}$, with direction given by Fleming's left-hand rule. Its maximum is BIl for perpendicular current and field, and its minimum is zero for parallel or antiparallel current and field. (ii) Wire A exerts a repulsive force of $1.0 \times 10^{-5} \text{ N}$ on the 10 cm length of wire B.

Quick Tip to Solve: For parallel wires use $F = \mu_0 I_A I_B l / (2\pi r)$, converting both length and separation to metres. Opposite currents mean repulsion.

- 33(a).** (i) (1) Write two points of difference between an interference pattern and a diffraction pattern.
(2) Name any two factors on which the fringe width in a Young's double-slit experiment depends.
(ii) In Young's double-slit experiment, the two slits are separated by a distance equal to 100 times the wavelength of light that passes through the slits. Calculate:
(1) the angular separation in radians between the central maximum and the adjacent maximum.
(2) the distance between these two maxima on a screen 50 cm from the slits. [5 marks]

Solution:

Concept:

- In Young's double-slit experiment, coherent waves from two narrow slits superpose. Bright fringes occur where the path difference is $d \sin \theta = m\lambda$, with slit separation d , wavelength λ and integer order m .
- For small angles and screen distance D much larger than d , the fringe width is $\beta = \lambda D / d$ and the angular fringe width is approximately λ / d .
- Single-slit diffraction comes from interference between secondary wavelets across one aperture. For slit width a , its minima obey $a \sin \theta = m\lambda$ for nonzero integer m .

Step 1: (i)(1) Compare the widths of the patterns In the usual small-angle Young's interference pattern, consecutive bright fringes are equally spaced, as are consecutive dark fringes. Bright and dark fringe bands have equal widths.

In a single-slit diffraction pattern, the central bright maximum extends between the first minima on its two sides. Its width is $2\lambda D / a$, approximately twice the width $\lambda D / a$ of each secondary bright band between successive minima. Thus all bright bands do not have the same width.

Step 2: Compare the intensities of the bright bands For ideal interference of two coherent waves with equal, constant individual intensities, all bright fringes have equal peak intensity. In single-slit diffraction, the central maximum is the brightest, and successive secondary maxima become much weaker as one moves away from the centre. These are the standard pattern comparisons; real slits of finite width can also impose a diffraction envelope on a double-slit interference pattern.

Step 3: (i)(2) Identify two factors affecting fringe width From

$$\beta = \frac{\lambda D}{d},$$

two factors are the wavelength λ and the slit-to-screen distance D . Increasing either one increases

the fringe width in direct proportion, with other quantities held fixed. The formula also shows that increasing slit separation d decreases the width.

Step 4: (ii)(1) Calculate the angular separation The given slit separation is $d = 100\lambda$. At the central maximum $m = 0$ and $\theta_0 = 0$. At the adjacent maximum $m = 1$, so

$$\sin \theta_1 = \frac{\lambda}{d} = \frac{1}{100} = 0.010.$$

Since the angle is small, $\sin \theta_1 \simeq \theta_1$ when measured in radians. Hence the angular separation is

$$\Delta\theta = \theta_1 - \theta_0 \simeq 0.010 \text{ rad.}$$

The exact inverse-sine value is approximately 0.0100002 rad, confirming the suitability of the small-angle approximation.

Step 5: (ii)(2) Find the separation on the screen Convert the screen distance to $D = 50 \text{ cm} = 0.50 \text{ m}$. The distance from the central maximum to the neighbouring maximum is one fringe width:

$$\begin{aligned}\Delta y = \beta &= \frac{\lambda D}{d} = \frac{D}{100} \\ &= \frac{0.50}{100} \text{ m} = 5.0 \times 10^{-3} \text{ m.}\end{aligned}$$

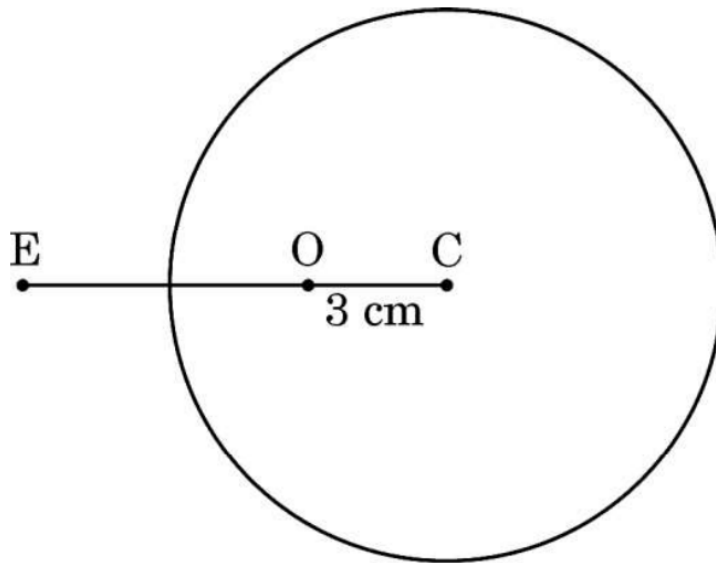
Equivalently, $\Delta y \simeq D\Delta\theta$. The same magnitude applies to the adjacent maximum on either side of the centre.

Step 6: Conclusion Interference fringes have uniform widths and, for ideal equal-intensity sources, equal bright-fringe peak intensities; single-slit diffraction has a central bright band twice as wide as the secondary bands and decreasing secondary peak intensities. Fringe width depends on wavelength and screen distance. The requested angular separation is 0.010 rad, and the screen separation is 5.0 mm.

Quick Tip to Solve: When slit separation is specified as 100λ , cancel the wavelength immediately: angular fringe width is $1/100$ radian and linear fringe width is $D/100$.

33(b). (i) A spherical surface of radius of curvature R separates two media of refractive indices n_1 and n_2 . A point object is placed in front of the surface at distance u in medium of refractive index n_1 and its image is formed by the surface at distance v , in the medium of refractive index n_2 . Derive a relation between u and v .

(ii) A solid glass sphere of radius 6.0 cm has a small air bubble trapped at a distance 3.0 cm from its centre C as shown in the figure. The refractive index of the material of the sphere is 1.5. Find the apparent position of this bubble when seen through the surface of the sphere from an outside point E in air. [5 marks]



Solution:

Concept:

- Snell's law is $n_1 \sin i = n_2 \sin r$. For paraxial rays, all angles are small, so $n_1 i = n_2 r$, with angles in radians.
- In the Cartesian sign convention, distances are measured from the pole P , positive in the direction of incident light. Thus $u = PO$, $v = PI$, and $R = PC$ are signed distances.

Step 1: (i) Set up the paraxial geometry Consider a convex refracting surface with object O on the left and centre of curvature C on the right of its pole P . Take a paraxial ray from O meeting the surface at A , at a small height h above the principal axis. Let it refract towards a real image I on the right. The normal at A is AC . Let α , β , and γ be the small positive angles that OA , AI , and AC , respectively, make with the principal axis. For this construction the angle of incidence is $i = \alpha + \gamma$, whereas the angle of refraction is $r = \gamma - \beta$.

Step 2: Apply Snell's law and introduce signed distances Substitution in the small-angle form of Snell's law gives

$$n_1(\alpha + \gamma) = n_2(\gamma - \beta), \quad n_1\alpha + n_2\beta = (n_2 - n_1)\gamma.$$

Since the ray is paraxial, the surface sag is negligible and the axial distances can be measured from P . In this construction $u < 0$, $v > 0$, and $R > 0$. Therefore

$$\alpha \simeq \frac{h}{-u}, \quad \beta \simeq \frac{h}{v}, \quad \gamma \simeq \frac{h}{R}.$$

On substituting these angles and cancelling h , the relation becomes

$$-\frac{n_1}{u} + \frac{n_2}{v} = \frac{n_2 - n_1}{R}.$$

This spherical-surface refraction equation also applies to other object, image and curvature arrangements when their Cartesian signs are used consistently. It assumes a small aperture and paraxial rays.

Step 3: (ii) Identify the surface viewed from E The observer E is to the left of the sphere, and the bubble lies between E and the centre C . Let P be the left surface. The bubble is $6.0 - 3.0 = 3.0$ cm inside that surface. Light travels from the glass towards E , so the positive direction is now to the left. Both the bubble and C lie to the right of P ; consequently

$$n_1 = 1.5, \quad n_2 = 1.0, \quad u = -3.0 \text{ cm}, \quad R = -6.0 \text{ cm}.$$

Only this glass-to-air surface is crossed by the rays reaching the observer.

Step 4: Calculate and interpret the image position Expressing every distance in centimetres, substitute in the relation derived above:

$$\begin{aligned} \frac{1}{v} - \frac{1.5}{-3.0} &= \frac{1.0 - 1.5}{-6.0}, \\ \frac{1}{v} + \frac{1}{2} &= \frac{1}{12}, \\ \frac{1}{v} &= -\frac{5}{12} \text{ cm}^{-1}, \quad v = -2.4 \text{ cm}. \end{aligned}$$

The negative sign places the image inside the glass, on the incident side of the surface; it is virtual. Its distance from C towards E is $6.0 - 2.4 = 3.6$ cm.

Step 5: Conclusion (i) $\frac{n_2}{v} - \frac{n_1}{u} = \frac{n_2 - n_1}{R}$. (ii) The bubble appears 2.4 cm inside the surface nearest E , or 3.6 cm from C towards E .

Quick Tip to Solve: Locate the observer first: measure the bubble's depth from the surface facing the observer, then assign signs in the direction in which light leaves the glass.

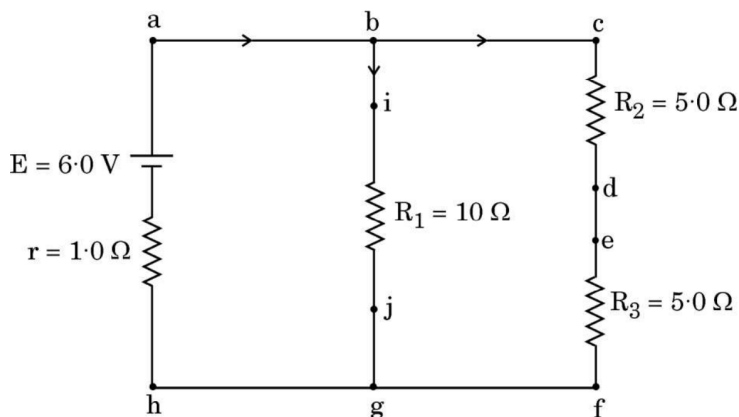
Section E (8 marks)

34(a). The following figure shows a circuit diagram. We can find the currents through and potential differences across different resistors using Kirchhoff's rules.

Answer the following questions based on the above:

Which points are at the same potential in the circuit?

[1 mark]



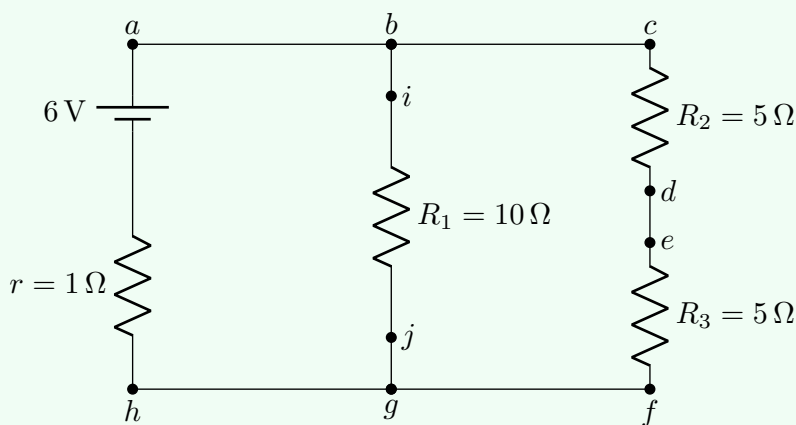
Solution:

Concept:

- All points joined by an ideal connecting wire have the same potential because its resistance is zero and $\Delta V = IR = 0$.
- A resistor or a cell can separate different potentials; a junction or a bend in an ideal wire cannot.

Step 1: Trace the upper and lower wires The points a, b, c are on the upper wire. Point i connects directly to b , before the resistor R_1 , so it has that same potential. The lower wire joins h, g, f , and point j connects directly to g , below R_1 . Thus j belongs to the lower group, not the upper one.

Step 2: Inspect the connection between the series resistors The points d and e are joined by a wire between R_2 and R_3 , so they are at the same potential. The resistors separate this middle group from the upper and lower groups. The diagram shows these connections explicitly.



Points connected by uninterrupted wire form an equipotential group.

Step 3: Conclusion The equipotential groups are $a = b = c = i$, $d = e$, and $f = g = h = j$, where equality denotes equal electric potential.

Quick Tip to Solve: Starting at each labelled point, follow only uninterrupted wire; stop at each resistor or cell to identify a new potential group.

34(b). Refer to the circuit diagram. What is the current through arm bg ?

[1 mark]

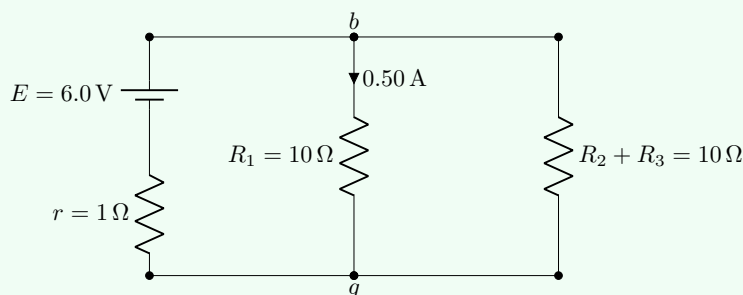
Solution:

Concept:

- Series resistances add, while for parallel branches $R_p^{-1} = R_a^{-1} + R_b^{-1}$. Parallel branches share a common terminal voltage.
- The internal resistance r of the cell is in series with the external network, so the cell supplies $I = E/(R_p + r)$.

Step 1: Reduce the external resistance The right-hand arm contains R_2 and R_3 in series, giving $5 + 5 = 10\Omega$. This arm is in parallel with the 10Ω resistance in arm bg . Hence

$$R_p = \frac{10 \times 10}{10 + 10} = 5\Omega.$$



Equivalent circuit: the two external arms each have resistance 10Ω .

Step 2: Include internal resistance and divide the current The total resistance seen by the emf is $5 + 1 = 6\Omega$, so the current supplied by the cell is $I = 6.0/6 = 1.0\text{ A}$. The two external arms have equal resistance, and the current divides equally. Equivalently, the terminal voltage is $6.0 - (1.0)(1.0) = 5.0\text{ V}$,

which gives $I_{bg} = 5.0/10 = 0.50 \text{ A}$. The positive terminal feeds the upper wire, fixing the downward current direction in bg .

Step 3: Conclusion The current through arm bg is 0.50 A , flowing from b to g .

Quick Tip to Solve: Combine the two right-hand resistors first. Equal parallel arms share the total current equally, but include the cell's internal resistance before finding that total.

34(c). Find the potential difference across resistance R_3 .

[2 marks]

Solution:

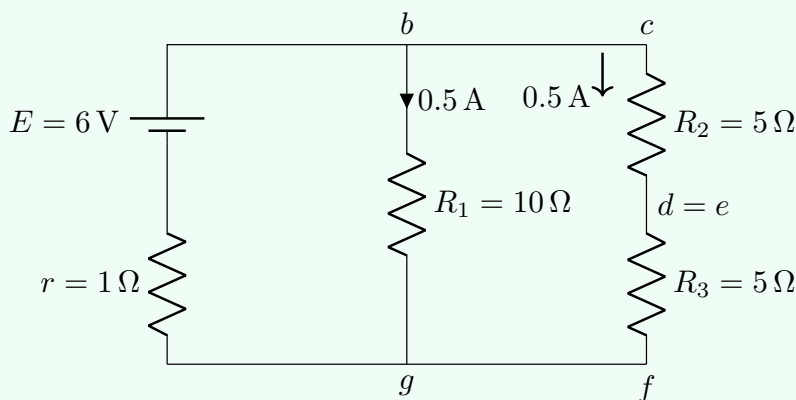
Concept:

- In a series branch, the same current flows through both resistors; in parallel branches, the potential difference is common.
- The cell terminal voltage is $V = E - Ir$, where E is its emf, r its internal resistance and I the total current. The voltage law gives $V_R = I_R R$.

Step 1: Reduce the external circuit The right-hand resistors are in series, since the same current passes successively through R_2 and R_3 . Their combined resistance is $R_{23} = 5 + 5 = 10 \Omega$. This branch is parallel to $R_1 = 10 \Omega$, between the common top and bottom wires. Hence

$$R_{\text{ext}} = \frac{10 \times 10}{10 + 10} = 5 \Omega.$$

The cell's internal resistance is in series with this external combination.



Equal currents flow through the two external branches.

Step 2: Find the current in the right-hand branch The total resistance including $r = 1 \Omega$ is 6Ω . Thus the current supplied by the cell is

$$I = \frac{E}{R_{\text{ext}} + r} = \frac{6}{5 + 1} = 1 \text{ A}.$$

The terminal voltage across the parallel branches is $V = E - Ir = 6 - 1 = 5 \text{ V}$. Each branch has resistance 10Ω , so the current through the series pair is $I_{23} = 5/10 = 0.5 \text{ A}$.

Step 3: Apply Ohm's law to the requested resistor For $R_3 = 5 \Omega$, use the branch current, rather than the total cell current:

$$V_{R_3} = I_{23} R_3 = (0.5)(5) = 2.5 \text{ V}.$$

Current flows from e towards f , so e is at the higher potential.

Step 4: Conclusion The potential difference across R_3 is $V_e - V_f = 2.5 \text{ V}$.

Quick Tip to Solve: Include the internal resistance first; then halve the terminal voltage because R_2 and R_3 are equal series resistors.

OR

34(c). Refer to the circuit diagram. What is the power dissipated in resistance R_2 ?

[2 marks]

Solution:

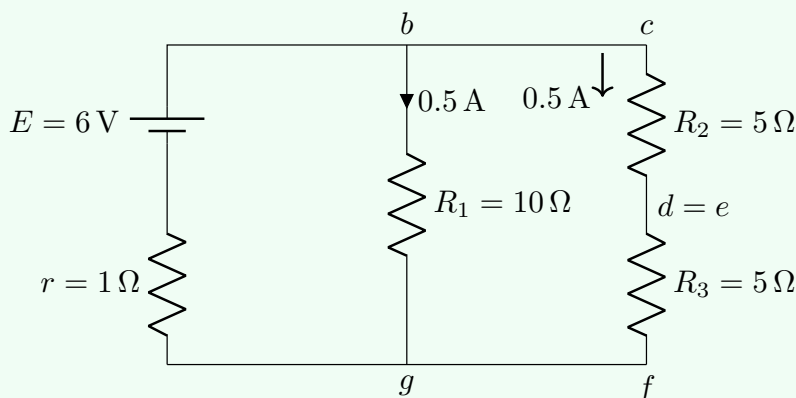
Concept:

- Resistors in series carry a common current. Parallel branches have the same terminal voltage.
- Joule heating power is $P = I_R^2 R$, where I_R is the current through the particular resistor, not necessarily the total cell current.

Step 1: Reduce the external circuit The right-hand resistors are in series, since the same current passes successively through R_2 and R_3 . Their combined resistance is $R_{23} = 5 + 5 = 10 \Omega$. This branch is parallel to $R_1 = 10 \Omega$, between the common top and bottom wires. Hence

$$R_{\text{ext}} = \frac{10 \times 10}{10 + 10} = 5 \Omega.$$

The cell's internal resistance is in series with this external combination.



Equal currents flow through the two external branches.

Step 2: Find the current in the right-hand branch The total resistance including $r = 1 \Omega$ is 6Ω . Thus the current supplied by the cell is

$$I = \frac{E}{R_{\text{ext}} + r} = \frac{6}{5 + 1} = 1 \text{ A}.$$

The terminal voltage across the parallel branches is $V = E - Ir = 6 - 1 = 5 \text{ V}$. Each branch has resistance 10Ω , so the current through the series pair is $I_{23} = 5/10 = 0.5 \text{ A}$.

Step 3: Calculate the heating power of R_2 The current through R_2 is the right-hand branch current 0.5 A . Therefore

$$P_{R_2} = I_{23}^2 R_2 = (0.5)^2 (5) = 1.25 \text{ W}.$$

As a check, its voltage drop is 2.5 V, giving the same value from $P = V^2/R = (2.5)^2/5$.

Step 4: Conclusion The power dissipated in R_2 is $\boxed{1.25 \text{ W}}$.

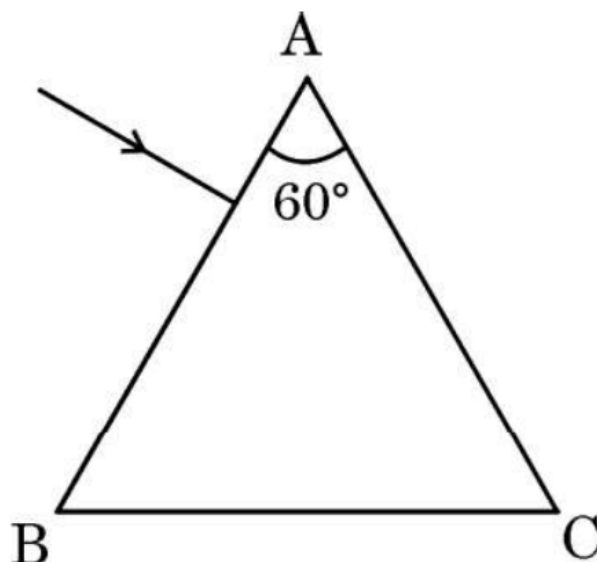
Quick Tip to Solve: Use the current through the series pair for $I^2 R_2$; using the full cell current would overestimate the power by a factor of four.

35(a). Strontium titanate is a rare oxide — a natural mineral found in Siberia. It is used as a substitute for diamond because its refractive index and critical angle are 2.41 and 24.5° , respectively, which are approximately equal to the refractive index and critical angle of diamond. It has all the properties of diamond. Even an expert jeweller is unable to differentiate between diamond and strontium titanate. A ray of light is incident normally on one face of an equilateral triangular prism ABC made of strontium titanate.

Answer the following questions based on the above:

Trace the path of the ray showing its passage through the prism.

[1 mark]



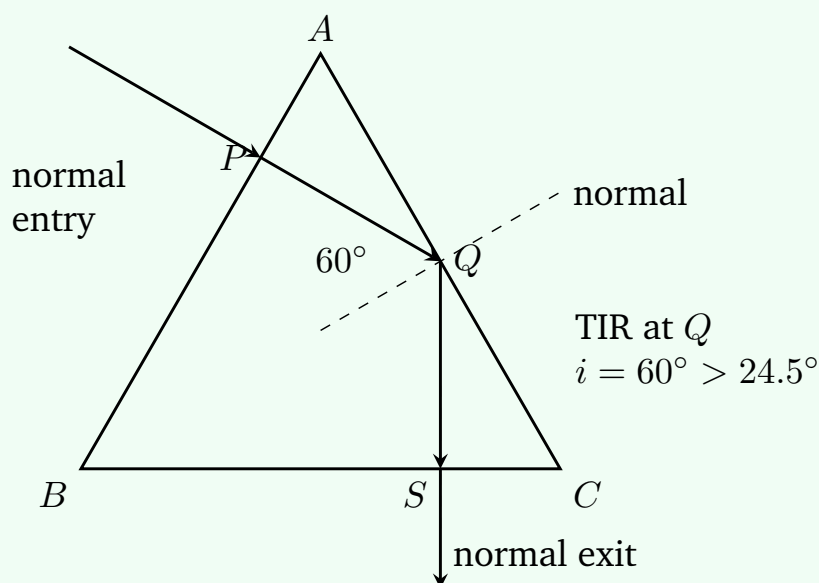
Solution:

Concept:

- At normal incidence, a ray enters a medium without deviation.
- Total internal reflection occurs from the denser medium to air when the incidence angle exceeds the critical angle 24.5° .

Step 1: Trace entry and reflection The ray enters face AB normally at P and continues straight to face AC at Q . In an equilateral prism the angle between the inward normals of these two faces gives an incidence angle $i = 60^\circ$ at AC . Since $60^\circ > 24.5^\circ$, the ray undergoes total internal reflection there.

Step 2: Trace the emergent ray By the law of reflection the reflected ray travels vertically down to face BC . It meets that face normally at S , so it emerges into air without further deviation. The arrows in the figure give the complete order of propagation.



Ray path through the equilateral strontium titanate prism.

Step 3: Conclusion The ray enters AB undeviated, undergoes total internal reflection at AC , and emerges normally through BC .

Quick Tip to Solve: Measure incidence from the normal: the second-face angle is 60° , whereas the angle to that face itself is 30° .

35(b). For the strontium titanate prism (refractive index 2.41), find the velocity of light through the prism. [1 mark]

Solution:

Concept:

- Absolute refractive index is $n = c/v$, where c is the speed in vacuum and v is the speed in the material.
- For a refractive index greater than unity, the speed in the medium is less than c .

Step 1: Rearrange the definition The given prism has $n = 2.41$. Solving the refractive-index relation for the speed in the prism gives $v = c/n$. The critical angle is not needed for this calculation.

Step 2: Substitute the given refractive index Using $c = 3.0 \times 10^8 \text{ m s}^{-1}$,

$$v = \frac{3.0 \times 10^8}{2.41} = 1.2448 \times 10^8 \text{ m s}^{-1}.$$

This is about $0.415c$, consistent with light travelling more slowly in the optically denser material.

Step 3: Conclusion The velocity magnitude (speed) of light through the prism is approximately $1.24 \times 10^8 \text{ m s}^{-1}$.

Quick Tip to Solve: For an absolute refractive index, divide the vacuum speed by n ; multiplying by n would incorrectly predict a speed above c .

35(c). Briefly explain two applications of total internal reflection.

[2 marks]

Solution:

Concept:

- Total internal reflection is the complete reflection of light back into an optically denser medium when it meets a rarer medium at an incidence angle greater than the critical angle.
- For refractive indices $n_1 > n_2$, the critical angle C satisfies $\sin C = n_2/n_1$. Incidence angles are measured from the normal.

Step 1: Explain light guidance in optical fibres An optical fibre has a transparent core surrounded by cladding of lower refractive index. Light entering within the suitable acceptance range strikes the core-cladding boundary at an angle greater than its critical angle. Repeated total internal reflections guide the light along the core, including through gentle bends. This enables transmission of optical signals in communication systems and light through fibres in medical endoscopes.

Step 2: Explain reflection by prisms A right-angled glass prism can turn a light beam through 90° . A ray entering normally through one of its perpendicular faces strikes the hypotenuse face at 45° . For ordinary glass in air, the critical angle is about 42° , so the ray undergoes total internal reflection and exits normally through the other perpendicular face. Such prisms are used in optical instruments such as periscopes to change the direction of light without a silvered reflecting surface.

Step 3: Conclusion Two applications are guiding light in optical fibres and changing the direction of a beam using totally reflecting prisms in optical instruments.

Quick Tip to Solve: For each application, identify the denser-to-rarer boundary and explain why the internal incidence angle exceeds the critical angle.

OR

35(c). Define total internal reflection of light. Give two conditions for it.

[2 marks]

Solution:

Concept:

- Refraction obeys Snell's law, $n_1 \sin i = n_2 \sin r$, where n_1, n_2 are the refractive indices of the incident and second media, and i, r are angles measured from the normal.
- For light travelling from an optically denser to a rarer medium, the critical angle C is the incidence angle for which the refracted ray grazes the boundary: $r = 90^\circ$, so $\sin C = n_2/n_1$.

Step 1: Define total internal reflection Total internal reflection is the phenomenon in which light incident at the boundary of an optically denser and an optically rarer medium is completely reflected back into the denser medium when the angle of incidence exceeds the critical angle. No refracted travelling ray emerges into the rarer medium under these conditions.

Step 2: State the required direction of travel The light must travel from an optically denser medium towards an optically rarer medium, meaning $n_1 > n_2$. Optical density refers here to refractive index, not to mass density. A ray travelling from air into glass cannot undergo total internal reflection at that entry boundary.

Step 3: State the required incidence angle The incidence angle in the denser medium must be strictly greater than the critical angle for the pair of media: $i > C$. At $i = C$, the refracted ray travels along

the boundary; this limiting case is not total internal reflection. For $i < C$, some light can be refracted into the second medium.

Step 4: Conclusion Total internal reflection is complete internal reflection at a boundary. Its two conditions are travel from an optically denser to a rarer medium and incidence at an angle greater than the critical angle.

Quick Tip to Solve: Check both conditions together: $n_1 > n_2$ and $i > C$. Equality $i = C$ gives a grazing refracted ray, not total internal reflection.