

CBSE Class 12 Physics Question Paper 2023 with Solution PDF-Set 55/1/2



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. Two identical circular coaxial coils A and B , arranged in vertical planes parallel to each other, carry currents in the same direction. If the distance between the coils is decreased at a constant rate, the current: [1 mark]

- (A) increases in A and decreases in B .
- (B) decreases in both A and B .
- (C) increases in both A and B .
- (D) remains same in both A and B .

Correct Answer: (B) decreases in both A and B .

Solution:

Concept:

- Mutual induction produces an emf in each coil when the magnetic flux linked with it due to the other coil changes.
- Lenz's law states that the induced current opposes the change in magnetic flux that produces it.

Step 1: Determine the change in flux Since the two coaxial coils carry currents in the same direction, their magnetic fields along the common axis reinforce one another. Bringing the coils closer increases the flux linked with each coil due to the other coil.

Step 2: Apply Lenz's law to both coils In each coil the induced emf drives a current opposite to its existing current, opposing the increase in linked flux. Thus both currents are reduced. The identical arrangement cannot produce opposite changes in the two coils, as option (A) suggests. An increase in both currents would aid the flux change, while unchanged currents would ignore induction.

Step 3: Conclusion The current decreases in both A and B . Hence, the correct option is (B).

Quick Tip to Solve: For approaching coaxial coils carrying currents in the same sense, first identify the increasing mutual flux, then oppose it using Lenz's law.

2. 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 flux produces displacement current, $I_d = \varepsilon_0 d\phi_E/dt$, where ϕ_E is electric flux and ε_0 is vacuum permittivity.

- During charging, displacement current between capacitor plates equals the conduction current in the connecting wires.

Step 1: Identify the current between the plates Charges accumulate on the plates but do not conduct through the insulating gap. The electric field and hence the electric flux in the gap change as the capacitor charges. The current associated with this changing flux is displacement current.

Step 2: Obtain the required expression For parallel plates of area A , neglecting edge effects, $E = Q/(\epsilon_0 A)$. Therefore,

$$\phi_E = EA = \frac{Q}{\epsilon_0}, \quad I_d = \epsilon_0 \frac{d\phi_E}{dt} = \frac{dQ}{dt}.$$

The coefficient is ϵ_0 , not μ_0 or either reciprocal. Consequently the expressions in (A), (B) and (D) do not represent this current.

Step 3: Conclusion The displacement current is $\epsilon_0 d\phi_E/dt$. Hence, the correct option is (C).

Quick Tip to Solve: Remember $\epsilon_0 \phi_E = Q$ for the plate gap; differentiating immediately gives the displacement current.

3. The minimum distance between an object and its real image formed by a convex lens of focal length f is: [1 mark]

- (A) f
- (B) $2f$
- (C) $3f$
- (D) $4f$

Correct Answer: (D) $4f$

Solution:

Concept:

- For a convex lens forming a real image, let $a = |u|$ and $b = v$ be positive object and image distances. The lens formula becomes $1/f = 1/a + 1/b$.
- The object and real image lie on opposite sides of the lens, so their separation is $D = a + b$.

Step 1: Express the separation using the lens formula Multiplying the lens formula by fab gives $ab = f(a + b) = fD$. Thus the product of the two positive distances is fixed by their sum and the focal length.

Step 2: Find the least possible separation Since $(a - b)^2 \geq 0$, we have $(a + b)^2 \geq 4ab$. Substituting $D = a + b$ and $ab = fD$ gives

$$D^2 \geq 4fD \Rightarrow D \geq 4f.$$

Equality is possible when $a = b = 2f$. The smaller separations f , $2f$ and $3f$ violate this inequality and cannot give a real image of a real object.

Step 3: Conclusion The minimum object-image distance is $4f$, attained when both are $2f$ from the lens. Hence, the correct option is (D).

Quick Tip to Solve: For minimum real object-image separation, put the object and image at the two $2f$ positions and add their distances.

4. A photon of energy 7 eV is incident on a metal surface having the work function of 3.75 eV. The stopping potential is: [1 mark]

- (A) 1.75 eV
- (B) 2.45 eV
- (C) 3.25 eV
- (D) 3.75 eV

Correct Answer: 3.25 V; option (C) has the intended numerical value, but every printed option incorrectly uses the energy unit eV.

Solution:

Concept:

- Einstein's photoelectric equation is $K_{\max} = E_{\gamma} - \phi$, where E_{γ} is photon energy and ϕ is the metal's work function.
- The stopping potential satisfies $eV_s = K_{\max}$, where e is the magnitude of electron charge. Potential is measured in volts, whereas eV measures energy.

Step 1: Calculate the maximum kinetic energy The photon first supplies the energy needed to liberate an electron. The remaining energy becomes its maximum kinetic energy:

$$K_{\max} = 7 - 3.75 = 3.25 \text{ eV.}$$

Step 2: Convert the energy into stopping potential An electron loses 1 eV of kinetic energy when stopped by a potential difference of 1 V. Therefore $V_s = 3.25 \text{ V}$. The values 1.75, 2.45 and 3.75 are inconsistent with the energy balance. Option (C) matches the numerical result, but its printed unit is eV rather than V, so none of the options is dimensionally correct as printed.

Step 3: Conclusion The stopping potential is 3.25 V. The intended numerical choice is (C), with its printed unit eV corrected to V; strictly, no printed option has the correct unit for potential.

Quick Tip to Solve: Subtract the work function from photon energy in eV; the resulting number is the stopping potential in volts, not in eV.

5. 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 energy levels are $E_n = -13.6/n^2 \text{ eV}$, where n is the principal quantum number.
- In absorption, photon energy equals the positive energy difference: $hc/\lambda = E_f - E_i$, where h is Planck's constant and c is the speed of light.

Step 1: Find the excitation energy The ground state is $n = 1$ and the final state is $n = 5$. Thus the

absorbed energy is

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

Step 2: Calculate the wavelength and compare Using $hc \simeq 1240 \text{ eV nm}$,

$$\lambda = \frac{1240}{13.056} \text{ nm} \simeq 94.98 \text{ nm}.$$

The other wavelengths, 975, 740 and 523 nm, correspond to much smaller photon energies and cannot excite a ground-state hydrogen atom to this level. This transition belongs to the ultraviolet region.

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

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

6. The atomic number of an atom represents:

[1 mark]

- (A) number of neutrons in nucleus.
- (B) total number of protons and electrons in the atom.
- (C) number of protons in nucleus.
- (D) total number of protons and neutrons in nucleus.

Correct Answer: (C) number of protons in nucleus.

Solution:

Concept:

- The atomic number Z is the number of protons in the nucleus and determines the identity of an element.
- The mass number is $A = Z + N$, where N is the neutron number. A neutral atom has Z electrons, but electrons are not counted in the definition of Z .

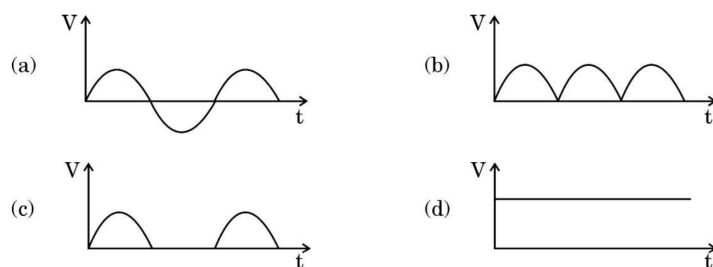
Step 1: Apply the definition of atomic number Each proton carries charge $+e$, so a nucleus of atomic number Z has charge $+Ze$. Atomic number therefore counts the positively charged protons in the nucleus.

Step 2: Distinguish the other particle counts Option (A) describes the neutron number N . In a neutral atom, the total number of protons and electrons in (B) is $2Z$. Option (D) describes the total nucleon count, or mass number A . Neither the neutron count nor the electron population changes the defining proton count of an element.

Step 3: Conclusion Atomic number represents the number of protons in the nucleus. Hence, the correct option is (C).

Quick Tip to Solve: Associate Z with nuclear charge and proton number; associate A with the sum of protons and neutrons.

7. 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 appreciable current in forward bias and blocks current in reverse bias.
- A single diode in series with an ac source and a load resistor acts as a half-wave rectifier. The load voltage is $V_L = IR_L$, where R_L is the load resistance.

Step 1: Follow the conducting and blocked half-cycles During the half-cycle that forward biases the diode, current flows through the resistor and a pulse appears across it. During the reverse-biased half-cycle, the current is approximately zero, so the load voltage is approximately zero. The output therefore contains alternate half-sine pulses separated by intervals of zero voltage.

Step 2: Compare the four printed waveforms Graph (c) shows exactly this half-wave output. Graph (a) retains both polarities of the input ac. Graph (b) represents full-wave rectification, which a single series diode cannot provide. Graph (d) is constant dc and would require smoothing; no smoothing component is specified here.

Step 3: Conclusion Graph (c) is the half-wave rectified voltage across the load. Hence, the correct option is (C).

Quick Tip to Solve: One series diode passes only one half of each ac cycle: look for pulses with a zero-voltage gap after every pulse.

8. 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, $\chi_m < 0$, so its induced magnetisation opposes the applied magnetic field.
- In a non-uniform magnetic field, a diamagnetic substance tends to move from a stronger-field region to a weaker-field region.

Step 1: Determine the effect near either pole The magnetic field is stronger near a pole of a bar magnet. The induced magnetic response of a diamagnetic substance opposes that field, and the substance is weakly repelled from the stronger-field region near the pole.

Step 2: Check what changes when the pole is reversed Replacing the north pole with the south pole reverses the applied field and also reverses the induced magnetisation. Their opposing relation remains the same, so the force still drives the material away from the stronger field. Attraction by both poles is characteristic of positive susceptibility, while different responses to the two poles would wrongly treat the substance as a fixed permanent dipole.

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

Quick Tip to Solve: For diamagnetic materials, use $\chi_m < 0$: they seek weaker magnetic fields, irrespective of which pole is brought near.

9. A circular coil of radius 8.0 cm and 40 turns is rotated about its vertical diameter with an angular speed of $\frac{25}{\pi}$ rad s⁻¹ in a uniform horizontal magnetic field of magnitude 3.0×10^{-2} 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 , flux linkage is $NBA \cos \omega t$, where B is the magnetic field and ω is angular speed.
- Faraday's law gives $\varepsilon = NBA\omega \sin \omega t$; its maximum magnitude is $\varepsilon_0 = NBA\omega$.

Step 1: Convert the radius and find the area The radius is $r = 8.0$ cm = 0.080 m. Thus $A = \pi r^2 =$

$0.0064\pi \text{ m}^2$. The vertical rotation axis is perpendicular to the horizontal field, so the flux varies over its full range.

Step 2: Use the printed angular speed The paper gives $\omega = 25/\pi \text{ rad s}^{-1}$, not 25 rad s^{-1} . Hence

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

The value rounds to 0.19 V; 0.12, 0.15 and 0.22 V do not follow from the given data.

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

Quick Tip to Solve: Keep the printed factor $1/\pi$ in angular speed: it cancels the π in the circular area.

10. 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:

- A trivalent impurity has three valence electrons, whereas silicon or germanium has four.
- Trivalent doping introduces acceptor levels and holes. Holes are the majority carriers in a p-type semiconductor.

Step 1: Identify the carrier produced by the dopant A dopant atom can complete only three of the four covalent bonds using its own valence electrons. It accepts an electron from a neighbouring bond, leaving a mobile hole. Thus holes outnumber free electrons after trivalent doping.

Step 2: Compare all the statements Creating extra mobile carriers raises conductivity and lowers resistance under the usual fixed conditions, so statement (A) is incorrect. The material becomes p-type, as in (B). Statement (C) describes electron majority carriers and is incorrect here. The dopant accepts an electron rather than donating one, so (D) is also incorrect.

Step 3: Conclusion The doped material is a p-type semiconductor. Hence, the correct option is (B).

Quick Tip to Solve: Three valence electrons mean an acceptor and a hole; five mean a donor and an extra electron.

11. 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 creates an energy level E_D just below the conduction-band edge E_C .
- The donor ionisation energy $E_C - E_D$ is much smaller than the full silicon band gap; only a small energy is needed to free the fifth electron.

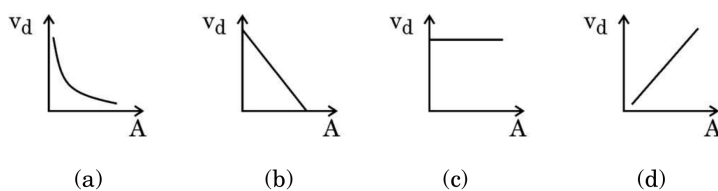
Step 1: Identify the relevant energy separation The question asks for the donor-to-conduction separation, not the valence-to-conduction band gap. Shallow donors in silicon have ionisation energies of a few hundredths of an electron volt, commonly about 0.05 eV. This is the 10^{-2} eV energy scale.

Step 2: Compare the listed scales Among the options, $0.01 \text{ eV} = 10^{-2} \text{ eV}$ represents the shallow donor scale. 1 eV is comparable to the full silicon band gap, while 10 eV is far too large. 0.1 eV represents the larger 10^{-1} eV scale rather than the standard donor-level scale requested.

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

Quick Tip to Solve: Distinguish the small donor ionisation energy from the roughly 1 eV full band gap.

12. 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:**

- For a metallic wire, $I = neAv_d$, where n is free-electron number density, e is the electron-charge magnitude and A is local cross-sectional area.
- In steady state, charge conservation requires the same current through every cross-section of an unbranched wire.

Step 1: Express drift speed in terms of area The material is the same along the wire, so n is constant. Since I is steady,

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

Therefore increasing the area reduces the magnitude of drift velocity inversely.

Step 2: Match the shape of the graph An inverse relation gives a decreasing rectangular hyperbola in the positive A - v_d plane, as shown in graph (a). Graph (b) is a straight-line decrease, not an inverse relation; graph (c) incorrectly keeps speed constant; graph (d) incorrectly makes speed rise with area.

Step 3: Conclusion The correct dependence is the rectangular hyperbola in graph (a). Hence, the correct option is (A).

Quick Tip to Solve: For one steady current in a uniform material, remember Av_d is constant, even when the wire tapers.

13. The masses of two cylindrical wires of copper are in the ratio of 1 : 3 and their lengths are in the ratio of 5 : 3. The ratio of their resistances will be: [1 mark]

- (A) 1 : 3
(B) 2 : 5
(C) 2 : 3
(D) 3 : 5

Correct Answer: No printed option is correct: the given mass and length ratios imply $R_1 : R_2 = 25 : 3$.

Solution:**Concept:**

- A cylindrical wire has resistance $R = \rho L/A$, where ρ is electrical resistivity, L is length and A is area.
- For mass m and mass density d , $m = dAL$. Wires made of the same copper have the same ρ and d , at the same temperature.

Step 1: Eliminate the cross-sectional area From $m = dAL$, the area is $A = m/(dL)$. Substitution into the resistance formula gives

$$R = \rho d \frac{L^2}{m}.$$

Thus resistance is proportional to length squared divided by mass, not merely to length or inverse mass.

Step 2: Calculate the printed ratio and check all options Using the printed values $m_1 : m_2 = 1 : 3$

and $L_1 : L_2 = 5 : 3$,

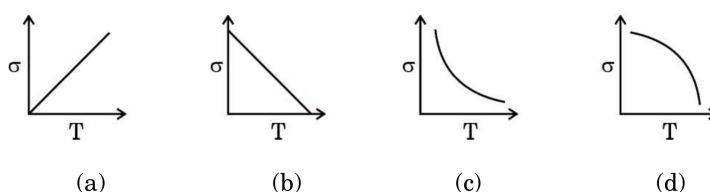
$$\frac{R_1}{R_2} = \left(\frac{5}{3}\right)^2 \frac{3}{1} = \frac{25}{3}.$$

Every printed option, $1 : 3$, $2 : 5$, $2 : 3$ and $3 : 5$, has its first term smaller than the second. None equals $25 : 3$. The data and options have been retained exactly as printed.

Step 3: Conclusion The printed data give $R_1 : R_2 = 25 : 3$. No listed option is correct, so a unique option cannot be selected.

Quick Tip to Solve: For wires of one material, use $R \propto L^2/m$; retaining the square avoids a common ratio error.

14. Which one of the following is the correct representation of variation of conductivity of a conductor with temperature? [1 mark]



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

Correct Answer: (C) Graph (c)

Solution:

Concept:

- For a metallic conductor, resistivity increases with temperature: $\rho(T) = \rho_0[1 + \alpha(T - T_0)]$, where $\alpha > 0$ over the usual temperature range.
- Conductivity is the reciprocal of resistivity: $\sigma = 1/\rho$. Increasing lattice vibrations impede electron motion as temperature rises.

Step 1: Express conductivity as a function of temperature Taking the reciprocal gives

$$\sigma(T) = \frac{\sigma_0}{1 + \alpha(T - T_0)}.$$

Thus conductivity decreases as temperature rises; its decrease gradually becomes less steep in this model.

Step 2: Compare the four curves Graph (c) shows the decreasing, upward-curving reciprocal dependence. Graph (a) increases and has the wrong trend. Graph (b) is a straight-line decrease rather than the reciprocal curve. Graph (d) becomes progressively steeper downward, which has the wrong

curvature. Therefore graph (c) is the correct representation among those printed.

Step 3: Conclusion Conductivity decreases with the reciprocal form shown in graph (c). Hence, the correct option is (C).

Quick Tip to Solve: Draw resistivity first as increasing roughly linearly, then take its reciprocal to identify conductivity.

15. 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, $\vec{E} = \frac{1}{4\pi\epsilon_0} \frac{2\vec{p}}{r^3}$, where $\vec{p}$ is its dipole moment.
- The force on a fixed point charge q is $\vec{F} = q\vec{E}$; for a fixed dipole and charge its magnitude is proportional to r^{-3} .

Step 1: Apply the short-dipole distance dependence The distance is much larger than the separation of the dipole charges, so the short-dipole field law applies. When the charge remains on the same axial ray and its distance doubles, the electric-field direction is unchanged.

Step 2: Compute the ratio of forces All factors except the distance cancel in the ratio:

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

Thus the force vector also becomes one eighth of its initial value. The factors $1/16$, $1/4$ and $1/2$ correspond to fourth-power, inverse-square and inverse-distance laws, respectively; none is the axial short-dipole law.

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

Quick Tip to Solve: A short dipole field falls as r^{-3} ; do not use the r^{-2} field law of an isolated point charge.

16. 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 having the same phase of oscillation at a given instant.
- For propagation from a point source in a homogeneous medium, equal distances correspond to equal travel times and hence equal phase at a given instant.

Step 1: Evaluate the assertion By the definition of a wavefront, every point on it has the same phase. Therefore the phase difference between any two of its points is zero, and Assertion (A) is true.

Step 2: Evaluate the reason In the standard homogeneous-medium source-wave picture used here, the wavefront consists of points reached after the same propagation time. These points are equally distant from the source and oscillate in phase. Thus Reason (R) is true in the intended setting.

Step 3: Check the explanatory link Equal propagation distances in the same medium give equal phase changes from the source. This directly explains why the points have zero phase difference. The reason is therefore an explanation of the assertion, not merely another true statement; options denying either truth or this link do not fit.

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

Quick Tip to Solve: For wavefront assertions, start from equal phase; use equal travel time in a homogeneous medium to explain it.

17. 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:

- Light transfers energy in photons: each photon has energy $E = h\nu$, where h is Planck's constant and ν is frequency.
- Einstein's equation is $K_{\max} = h\nu - \phi$, where $\phi = h\nu_0$ is the metal's work function and ν_0 is the threshold frequency.

Step 1: Judge the assertion Assertion (A) is true. Photoemission has a threshold frequency, is essentially instantaneous, and gives a maximum electron kinetic energy that depends on frequency. These observations are explained by one photon transferring its energy to one electron.

Step 2: Judge the reason Reason (R) is true. For fixed frequency above threshold and unchanged collecting conditions, increasing intensity increases the number of incident photons per second and hence the number of emitted electrons per second. The photoelectric current therefore increases in proportion to intensity.

Step 3: Check the explanatory link The current-intensity relation alone does not establish the particle nature of light; a greater energy input could also be associated with a larger emission rate in a classical argument. The decisive evidence concerns threshold frequency and electron energy. Thus the true reason does not explain the assertion; choices (C) and (D) incorrectly declare a statement false.

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

Quick Tip to Solve: Distinguish the number of photoelectrons (set by intensity) from their maximum energy (set by frequency).

18. 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:

- For a weak magnetic material, $M = \chi_m H$ and $\mu_r = 1 + \chi_m$, where χ_m is magnetic susceptibility.
- Diamagnetic substances have $\chi_m < 0$ and $\mu_r < 1$; their induced magnetisation opposes the applied field.

Step 1: Judge the assertion Assertion (A) is false. Copper is diamagnetic, so the magnetic field inside a copper bar is slightly reduced relative to the applied field. Field lines tend to be displaced out of the bar and are less dense inside, rather than concentrated there.

Step 2: Judge the reason Reason (R) is also false. Copper is a diamagnetic substance, not a paramagnetic substance. Paramagnets have positive susceptibility and acquire magnetisation along the applied field, which is the opposite of the response of copper.

Step 3: Check the explanatory link Since both statements are false, no valid explanatory relation exists between them. The choices requiring a true assertion, namely (A), (B) and (C), are therefore excluded. Do not confuse copper's good electrical conductivity with its magnetic classification.

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

Quick Tip to Solve: For copper remember $\chi_m < 0$: field lines become slightly less dense inside the specimen.

Section B (14 marks)

19. 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 moves charge carriers from higher to lower concentration across a newly formed junction.
- The exposed fixed ions establish a depletion region and an electric field; this field drives a drift current opposite to diffusion current.

Step 1: Explain diffusion and the space charge Initially, electrons diffuse from the n-side to the p-side, while holes diffuse from the p-side to the n-side. Near the junction they recombine, leaving immobile positive donor ions on the n-side and negative acceptor ions on the p-side. The region loses mobile majority carriers and forms the depletion layer. Both diffusion processes contribute to conventional diffusion current from p to n.

Step 2: Explain drift and equilibrium The fixed space charge produces an electric field directed from the n-side towards the p-side and an associated potential barrier. This field opposes further majority-carrier diffusion and sweeps thermally generated minority carriers across the junction: electrons towards n and holes towards p. Their conventional drift current flows from n to p. As the barrier develops, diffusion decreases until, at thermal equilibrium, the opposing currents have equal magnitudes:

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

The barrier then has a steady value, although both microscopic carrier processes continue.

Step 3: Conclusion Diffusion creates the depletion-layer space charge and potential barrier; the resulting field produces an opposing drift current. Their balance establishes equilibrium with zero net junction current.

Quick Tip to Solve: Keep the electric-field direction n to p distinct from majority-carrier diffusion current, which is p to n.

20(a). Differentiate between intrinsic and extrinsic semiconductors.

[2 marks]

Solution:

Concept:

- An intrinsic semiconductor is chemically pure; an extrinsic semiconductor is deliberately doped with a small controlled amount of suitable impurity.
- Let n and p denote the electron and hole concentrations. Charge transport depends on their populations and mobilities.

Step 1: Compare composition and carrier populations In an intrinsic semiconductor such as pure silicon or germanium, thermal generation produces electrons and holes in pairs, so $n = p = n_i$. Neither type is a majority carrier. In an extrinsic semiconductor, donor or acceptor impurities change the carrier population: n-type material has electrons as majority carriers and holes as minority carriers, whereas p-type material has holes as majority carriers and electrons as minority carriers. Thus $n \neq p$ in the doped material under the usual operating conditions.

Step 2: Compare the origin of conductivity Intrinsic conductivity arises from thermally generated electron-hole pairs and is relatively small at room temperature. Extrinsic conductivity is enhanced by doping: pentavalent donors provide extra mobile electrons in silicon or germanium, while trivalent acceptors provide holes. At the same temperature, appropriately doped material generally conducts better than the pure host. Both electrons and holes can contribute to conduction in either case; doping does not make the whole crystal electrically charged.

Step 3: Conclusion Intrinsic semiconductors are pure with equal electron and hole concentrations; extrinsic semiconductors are doped and have distinct majority and minority carriers, usually with higher conductivity.

Quick Tip to Solve: Use two paired distinctions: pure versus doped, then equal carrier populations versus majority and minority carriers.

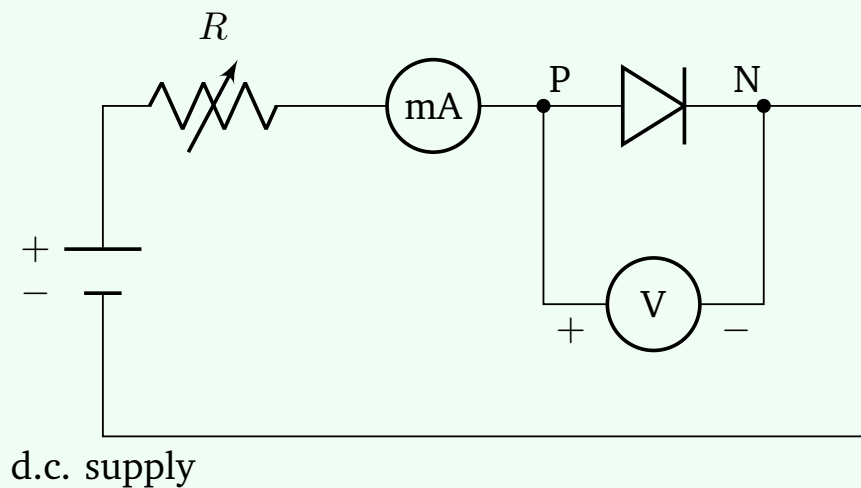
20(b). Draw the circuit arrangement for studying the V - I characteristics of a p-n junction diode in forward bias and reverse bias. Show the plot of V - I characteristic of a silicon diode. [2 marks]

Solution:

Concept:

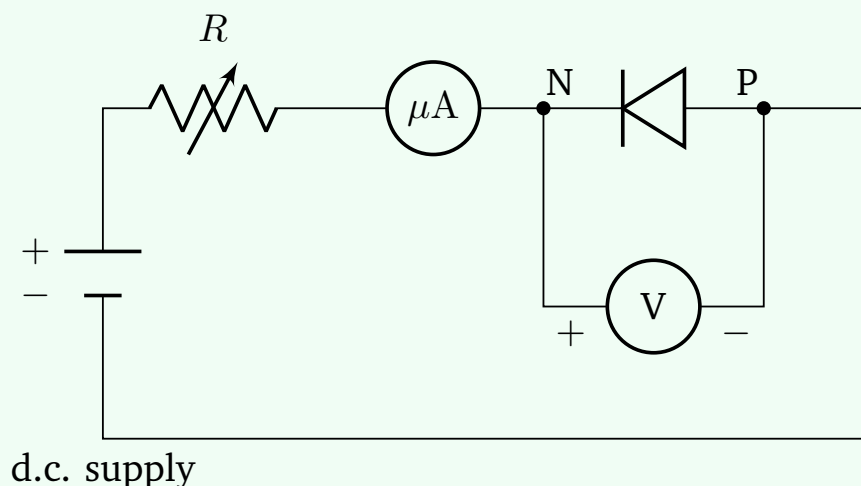
- Forward bias connects the p-side to the supply positive terminal and the n-side to its negative terminal; reverse bias interchanges these connections.
- An ammeter measures series current and a voltmeter measures the potential difference across the diode. A series variable resistance R controls and limits current.

Step 1: Arrange the forward-bias circuit Connect the silicon diode with its P terminal towards the positive terminal of the d.c. supply, as shown. Use a milliammeter in series and a voltmeter across the diode. Increase the applied voltage gradually using the variable resistance and note corresponding diode voltage and current readings. The voltmeter positive terminal is connected to P.



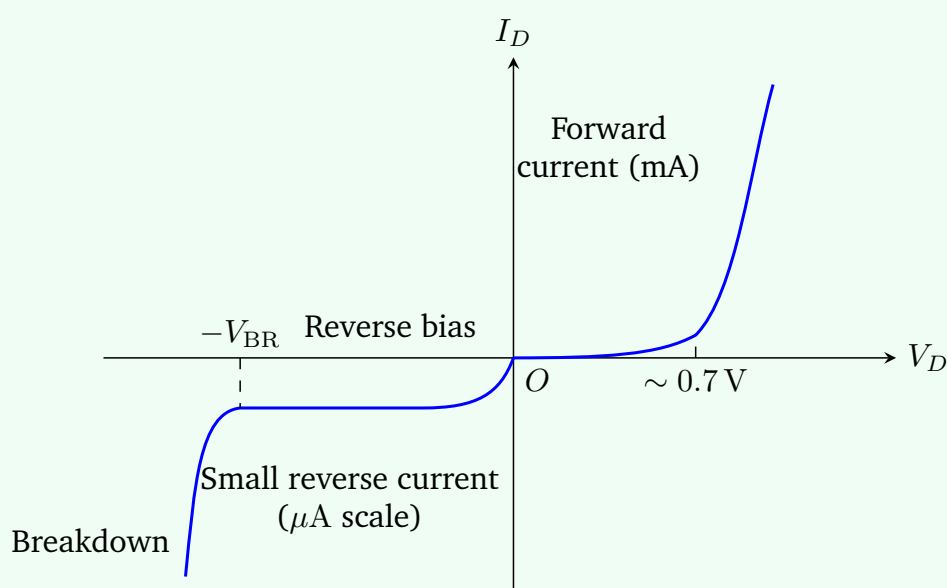
Forward bias: P connected towards the positive terminal; R limits the current.

Step 2: Arrange the reverse-bias circuit Reverse the diode so that N is connected towards the positive supply terminal. Replace the milliammeter by a microammeter because the reverse current is very small. The voltmeter remains across the diode with its positive terminal towards N. Vary the reverse voltage and record the reverse current, keeping within the safe range of the diode.



Reverse bias: N connected towards the positive terminal; the small reverse current is measured in microamperes.

Step 3: Plot and explain the characteristic Use signed diode voltage $V_D = V_P - V_N$ on the horizontal axis and signed conventional current from P to N on the vertical axis. In forward bias, current is initially small and then rises rapidly beyond the approximate silicon knee voltage 0.7 V. In reverse bias, a very small, nearly constant reverse saturation current flows until breakdown, after which the reverse current rises sharply in magnitude. The curve uses different practical scales for the two regions so that the small reverse current is visible.



Schematic silicon characteristic (unequal current and voltage scales in the two bias regions).

Step 4: Conclusion The two arrangements and the silicon V - I characteristic are shown. Forward conduction rises rapidly near 0.7 V; reverse current stays small until breakdown.

Quick Tip to Solve: Check P to positive for forward bias, N to positive for reverse bias, and use a microammeter for reverse current.

21. 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 force on a particle of charge q moving with velocity $\vec{v}$ is $\vec{F} = q(\vec{v} \times \vec{B})$. Hence its acceleration is $\vec{a} = (q/m)(\vec{v} \times \vec{B})$.
- Only the magnetic-field component perpendicular to the velocity contributes. For the right-handed coordinate axes, $\hat{i} \times \hat{i} = 0$ and $\hat{i} \times \hat{j} = \hat{k}$.

Step 1: Evaluate the vector product The velocity is along the positive x -axis. The 0.4 T component is parallel to it and produces no force; the 0.3 T component is perpendicular. Therefore,

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

Step 2: Use the given charge-to-mass ratio An alpha particle is positively charged, so the acceleration has the same direction as $\vec{v} \times \vec{B}$. Substitution gives

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

This is the acceleration for the stated velocity on entering the magnetic-field region.

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

Quick Tip to Solve: When velocity is along $\hat{i}$, discard the parallel B_x term before taking the cross product; $\hat{i} \times \hat{j}$ points along $+\hat{k}$.

22. A plane electromagnetic wave propagates in vacuum along x -axis.

(a) Give the direction of electric field and magnetic field vectors.

(b) E_0 and B_0 are the magnitudes of electric and magnetic fields respectively in a plane electromagnetic wave. Find the ratio of energy densities of electric field and magnetic field.

[2 marks]

Solution:

Concept:

- An electromagnetic wave is transverse: its electric and magnetic fields are perpendicular to each other and to the propagation direction. The direction of propagation is that of $\vec{E} \times \vec{B}$.
- In vacuum, $E_0 = cB_0$ and $c^2 = 1/(\mu_0 \epsilon_0)$. The field energy densities are $u_E = \epsilon_0 E^2/2$ and $u_B = B^2/(2\mu_0)$.

Step 1: (a) Specify a consistent pair of field directions Both fields lie in the yz -plane, perpendicular to the x -axis. For propagation along $+x$, one possible choice is $\vec{E}$ along $+y$ and $\vec{B}$ along $+z$, since $\hat{j} \times \hat{k} = \hat{i}$. More generally, any mutually perpendicular pair in that plane with the same cross-product direction is allowed; the question does not fix the polarization.

Step 2: (b) Compare the energy densities Using the field amplitudes, the ratio is

$$\frac{u_E}{u_B} = \frac{\varepsilon_0 E_0^2/2}{B_0^2/(2\mu_0)} = \varepsilon_0 \mu_0 \frac{E_0^2}{B_0^2} = \varepsilon_0 \mu_0 c^2 = 1.$$

The electric and magnetic fields oscillate in phase, so their instantaneous energy densities are equal. Their time-averaged energy densities are also equal; averaging introduces the same factor into both.

Step 3: Conclusion For propagation along $+x$, a possible pair is $\vec{E} \parallel \hat{j}$, $\vec{B} \parallel \hat{k}$. The electric-to-magnetic energy-density ratio is $u_E : u_B = 1 : 1$.

Quick Tip to Solve: Check field directions with $\vec{E} \times \vec{B}$, and replace E_0/B_0 by c before simplifying an energy-density ratio.

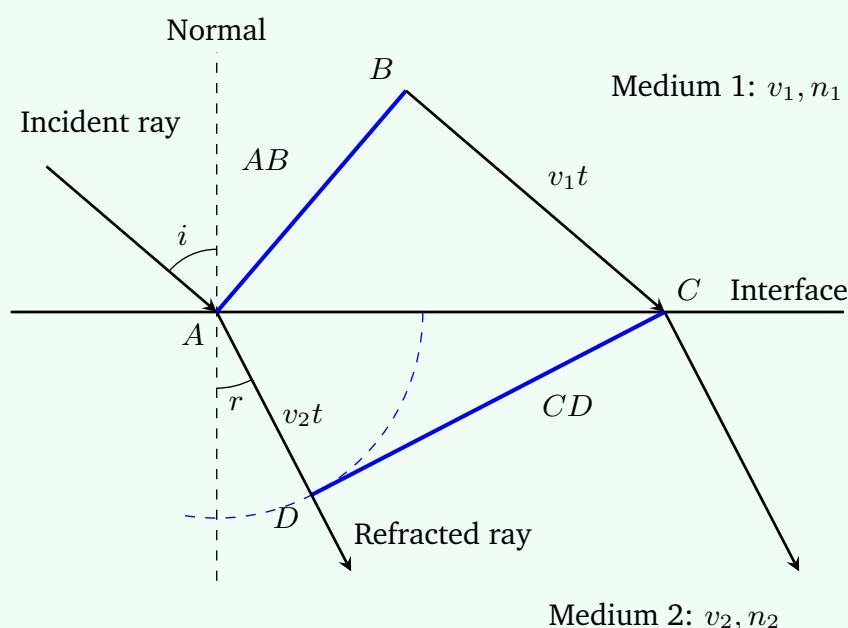
23(a). Using Huygens' principle, draw a ray diagram showing the propagation of a plane wave refracting at a plane surface separating two media. Also verify Snell's law of refraction. [2 marks]

Solution:

Concept:

- Huygens' principle states that every point on a wavefront emits secondary wavelets. The common forward tangent to them gives the new wavefront; rays are normal to wavefronts.
- If light travels with speeds v_1 and v_2 in media of refractive indices n_1 and n_2 , then $v_1 = c/n_1$ and $v_2 = c/n_2$. Incidence and refraction angles are measured from the normal.

Step 1: Construct the refracted wavefront Let the incident plane wavefront AB reach the plane interface first at A . In time t , the disturbance at B reaches C , so $BC = v_1 t$. Meanwhile a secondary wavelet from A has radius $AD = v_2 t$ in the second medium. The tangent CD from C to this wavelet is the refracted plane wavefront. The refracted ray AD is perpendicular to CD . The sketch shows $v_2 < v_1$, hence bending towards the normal.



Huygens' construction at a plane interface; AB and CD are wavefronts, while arrows show rays.

Step 2: Obtain Snell's law from the two right triangles Since each ray is normal to its wavefront,

$\angle BAC = i$ and $\angle ACD = r$. The right triangles ABC and ADC share hypotenuse AC , giving

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

Dividing these equations eliminates the common distance and time:

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

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

Quick Tip to Solve: Use the common hypotenuse AC : write $\sin i = BC/AC$ and $\sin r = AD/AC$, then divide to cancel AC and t .

OR

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

Solution:

Concept:

- A refracting telescope uses an objective lens to collect and focus light, whereas a reflecting telescope uses a concave primary mirror. The choice of objective affects image quality and the practical aperture.
- The light-gathering power is proportional to the objective area, hence to D^2 , where D is the aperture diameter. The minimum resolvable angle is approximately $1.22\lambda/D$ for wavelength λ .

Step 1: Explain the absence of chromatic aberration The refractive index of a lens material varies with wavelength, so different colours have different focal lengths in a simple refracting objective. This produces coloured fringes and reduces image sharpness. A mirror focuses light by reflection, whose geometrical law is the same for all wavelengths. Thus the reflecting objective is free from chromatic aberration and brings different colours to a common focus.

Step 2: Explain why a larger aperture is practical A large primary mirror can be supported from its back. A large objective lens must transmit the light through its body and is supported mainly around its edge, making a heavy lens harder to support without distortion. Mirrors therefore permit much larger practical apertures. The larger area collects more light from faint astronomical objects, and the larger diameter reduces the diffraction-limited angular separation, improving resolving power.

Step 3: Conclusion A reflecting telescope is preferred because its objective has no chromatic aberration and can have a large, mechanically supported aperture, giving greater light-gathering and resolving powers.

Quick Tip to Solve: Link each reason to its cause: reflection avoids colour dispersion, while support behind the mirror makes a larger light-collecting aperture practical.

24. A double-convex lens of power 4 D is manufactured from a glass of refractive index 1.5. What is the radius of curvature of each face of this lens if both faces have the same radius of curvature? [2 marks]

Solution:

Concept:

- For a thin lens in air, the lens maker's formula is $P = 1/f = (\mu - 1)(1/R_1 - 1/R_2)$, where μ is the glass refractive index and the radii are in metres when power P is in dioptres.
- For an equiconvex lens with light travelling from left to right, the Cartesian sign convention gives $R_1 = +R$ and $R_2 = -R$, where R is the common radius magnitude.

Step 1: Insert the signed radii The centres of curvature of the two surfaces lie on opposite sides of their respective poles. Equal curvature magnitudes therefore do not mean equal signed radii. With $\mu = 1.5$, the lens maker's formula becomes

$$P = (1.5 - 1) \left(\frac{1}{R} - \frac{1}{-R} \right) = \frac{2(0.5)}{R} = \frac{1}{R}.$$

Step 2: Calculate the common radius The double-convex glass lens is converging in air, so its given power is positive: $P = +4 \text{ m}^{-1}$. Thus

$$R = \frac{2(\mu - 1)}{P} = \frac{2(1.5 - 1)}{4} \text{ m} = 0.25 \text{ m} = 25 \text{ cm}.$$

As a consistency check, its focal length is $f = 1/P = 0.25 \text{ m}$; for this particular refractive index, an equiconvex thin lens has $f = R$.

Step 3: Conclusion Each face has radius of curvature of magnitude 25 cm. The signed radii are $R_1 = +25 \text{ cm}$ and $R_2 = -25 \text{ cm}$.

Quick Tip to Solve: For equal convex faces, use opposite signs for the radii first; then $P = 2(\mu - 1)/R$ gives the common magnitude directly in metres.

25. Calculate the wavelength of the second line of Lyman series in a spectrum of hydrogen atom. (Take Rydberg constant, $R = 1.1 \times 10^7 \text{ m}^{-1}$.) [2 marks]

Solution:

Concept:

- The Lyman series of hydrogen consists of emission transitions ending at the ground state $n_1 = 1$; its first line is $n_2 = 2$ to $n_1 = 1$.
- The Rydberg formula is $1/\lambda = R(1/n_1^2 - 1/n_2^2)$, where λ is the emitted wavelength, R is the Rydberg constant and $n_2 > n_1$.

Step 1: Identify the second Lyman transition Successive Lyman lines arise from upper levels $n_2 = 2, 3, 4, \dots$, all ending at $n_1 = 1$. Therefore the second line is the transition $n_2 = 3 \rightarrow n_1 = 1$, not the transition from $n = 2$.

$$\frac{1}{\lambda} = R \left(1 - \frac{1}{3^2} \right) = \frac{8R}{9}.$$

Step 2: Substitute the stated Rydberg constant Using the value given in the question, $R = 1.1 \times$

10^7 m^{-1} , gives

$$\begin{aligned}\lambda &= \frac{9}{8(1.1 \times 10^7)} \text{ m} \\ &= 1.0227 \times 10^{-7} \text{ m} \\ &= 102.27 \text{ nm}.\end{aligned}$$

The conversion uses $1 \text{ nm} = 10^{-9} \text{ m}$. This wavelength lies below the visible range, consistent with the ultraviolet character of the Lyman series.

Step 3: Conclusion The wavelength of the second Lyman line is $\lambda \approx 1.02 \times 10^{-7} \text{ m} \approx 102 \text{ nm}$, corresponding to the $3 \rightarrow 1$ transition.

Quick Tip to Solve: For the second line of any hydrogen series, take the upper level two above the fixed lower level; for Lyman this means $3 \rightarrow 1$.

Section C (15 marks)

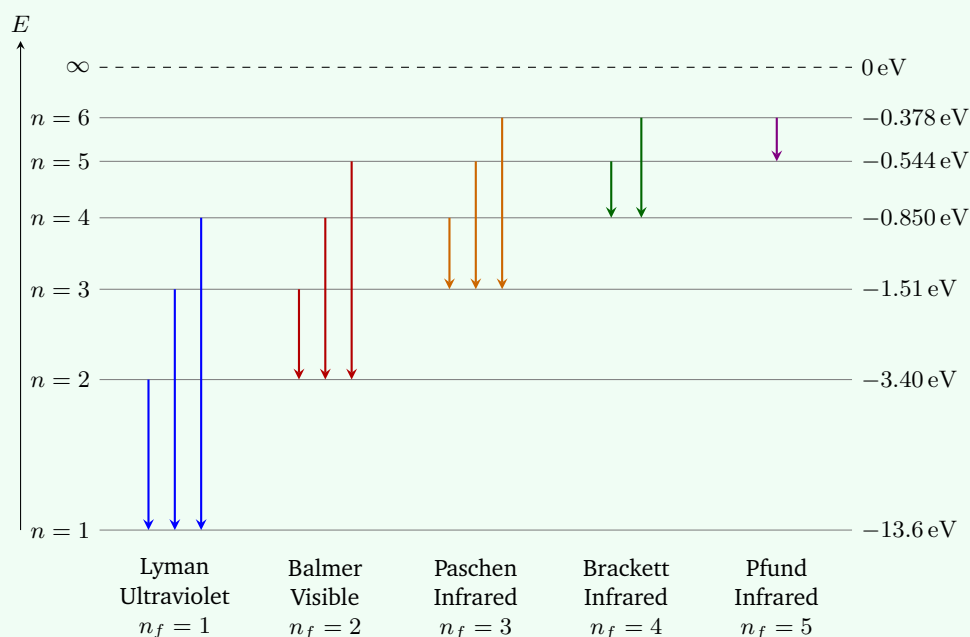
26(a). Draw the energy level diagram for hydrogen atom. Mark the transitions corresponding to the series lying in the ultraviolet region, visible region and infrared region. [3 marks]

Solution:

Concept:

- Hydrogen has discrete stationary energies $E_n = -13.6/n^2 \text{ eV}$, where $n = 1, 2, 3, \dots$ is the principal quantum number. The zero of energy is the ionisation limit $n \rightarrow \infty$.
- A downward transition emits a photon with $h\nu = E_{n_i} - E_{n_f} > 0$, where $n_i > n_f$. A spectral series groups all transitions with the same final level n_f .

Step 1: Construct the hydrogen energy levels The ground state has energy -13.6 eV . The next levels are -3.40 eV , -1.51 eV , -0.85 eV , -0.544 eV and -0.378 eV for $n = 2, 3, 4, 5, 6$, respectively. The levels crowd together towards $E = 0$, the ionisation limit. The schematic below shows representative downward transitions; the vertical scale is expanded near the higher levels to make the arrows readable.



Hydrogen energy levels and representative emission transitions (schematic, not to scale).

Step 2: Associate each series with its final level Transitions $n_i = 2, 3, 4, \dots \rightarrow 1$ form the **Lyman series in the ultraviolet region**. Transitions $n_i = 3, 4, 5, \dots \rightarrow 2$ form the **Balmer series**, whose prominent lines lie in the **visible region**; the high-order lines extend into the near ultraviolet. Transitions $n_i = 4, 5, 6, \dots \rightarrow 3$ form the **Paschen series in the infrared region**. The Brackett series ($n_i \geq 5 \rightarrow 4$) and Pfund series ($n_i \geq 6 \rightarrow 5$) also lie in the infrared region. Each series contains further lines beyond the representative arrows shown.

Step 3: Conclusion The required identifications are **Lyman: ultraviolet; Balmer: visible; Paschen: infrared**. Brackett and Pfund are further infrared series, ending at $n = 4$ and $n = 5$, respectively.

Quick Tip to Solve: Label each series by where its arrows end: $n_f = 1, 2, 3$ gives Lyman, Balmer and Paschen. Draw emission arrows downward, towards more negative energy.

OR

26(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]

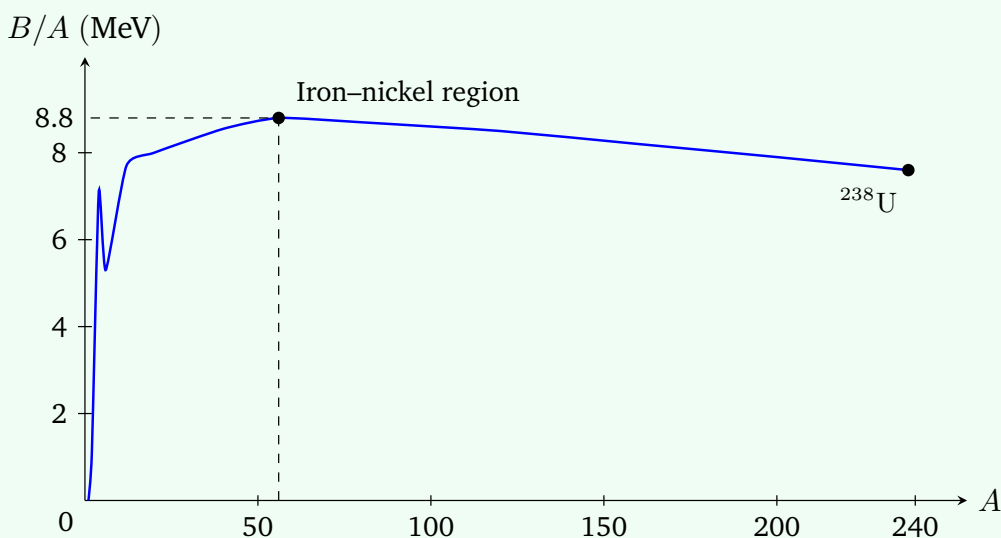
Solution:

Concept:

- Binding energy B is the energy needed to separate a nucleus into its individual nucleons. Binding energy per nucleon is B/A , where A is the mass number.
- A larger value of B/A signifies stronger average binding and greater nuclear stability. Nuclear reactions release energy when the total binding energy of their products exceeds that of their reactants.

Step 1: Draw the binding-energy curve Plot mass number A on the horizontal axis and binding energy per nucleon B/A , in MeV, on the vertical axis. The schematic curve below rises rapidly for

light nuclei, reaches its broad maximum near the iron–nickel region, and falls slowly towards the heaviest nuclei. The small irregularities among light nuclei are represented schematically.



Schematic variation of binding energy per nucleon with mass number.

Step 2: State two features of the curve First, B/A rises rapidly for small mass numbers and attains approximately 8.8 MeV near $A \approx 56$. Nuclei in this region are particularly stable. Second, beyond this region the curve decreases slowly: medium-mass nuclei have nearly constant binding energy per nucleon, around 8 MeV, while very heavy nuclei such as uranium have about 7.6 MeV per nucleon.

Step 3: Explain why fusion of light nuclei releases energy When suitable light nuclei combine to form a heavier nucleus on the rising part of the curve, the product has a higher binding energy per nucleon. Since the total number of nucleons is conserved, the total binding energy increases. The corresponding decrease in rest mass appears as released energy:

$$Q = B_{\text{products}} - B_{\text{reactants}} = \Delta m c^2 > 0.$$

Thus fusion can take light nuclei towards a more tightly bound state. High temperature is required to help the positively charged nuclei overcome their electrostatic repulsion; the favourable energy balance alone does not make fusion spontaneous at ordinary temperatures.

Step 4: Conclusion The curve has a broad maximum of about 8.8 MeV per nucleon near $A \approx 56$, followed by a slow decline. Suitable light nuclei release energy by fusion because their products have greater binding energy per nucleon.

Quick Tip to Solve: For fusion, compare the initial and final positions on the rising side of the curve: moving to larger binding energy per nucleon means energy is released.

27. The threshold wavelength for a metal is $3315 \text{ \AA}$. What should be the wavelength of light incident on the metal surface so that the maximum kinetic energy of the emitted photoelectrons be 1.25 eV ? [3 marks]

Solution:

Concept:

- The threshold wavelength λ_0 is the longest wavelength capable of ejecting electrons. The work function is $\phi = hc/\lambda_0$, where h is Planck's constant and c is the speed of light.
- Einstein's photoelectric equation is $K_{\max} = hc/\lambda - \phi$, where λ is the incident wavelength and $K_{\max}$ is the maximum kinetic energy of an emitted electron.

Step 1: Convert the given threshold wavelength The printed data are $\lambda_0 = 3315 \text{ \AA}$ and $K_{\max} = 1.25 \text{ eV}$. Since $1 \text{ \AA} = 0.1 \text{ nm}$, the threshold wavelength is 331.5 nm . Using $hc \approx 1240 \text{ eV nm}$, the work function is

$$\phi = \frac{1240}{331.5} \text{ eV} \approx 3.741 \text{ eV}.$$

At this threshold the emitted electron has zero maximum kinetic energy: the entire photon energy is used to escape the metal.

Step 2: Find the required incident photon energy To provide the specified kinetic energy, the incident photon must supply both the work function and the kinetic energy. Thus

$$E_\gamma = \phi + K_{\max} = 3.741 + 1.25 = 4.991 \text{ eV}.$$

The energies are both expressed in electronvolts, so they can be added directly. Subtracting the kinetic energy from the work function would violate the photoelectric energy balance.

Step 3: Calculate the incident wavelength and check its direction From $E_\gamma = hc/\lambda$,

$$\lambda = \frac{1240 \text{ eV nm}}{4.991 \text{ eV}} \approx 248.5 \text{ nm} = 2.485 \times 10^{-7} \text{ m}.$$

This is shorter than 331.5 nm , as required: a shorter wavelength gives more photon energy and leaves a positive kinetic energy after the electron escapes.

Step 4: Conclusion The incident light should have wavelength $\lambda \approx 2.49 \times 10^{-7} \text{ m}$, equivalently about 248.5 nm or $2485 \text{ \AA}$.

Quick Tip to Solve: Convert the threshold to nanometres and use $hc = 1240 \text{ eV nm}$; add the required kinetic energy to the work function before finding the new wavelength.

28. The primary and the secondary coils of an ideal step-down transformer consist of 650 and 25 turns respectively. When the primary coil of this transformer is connected to 240 V mains, the current in the primary coil is 1.5 A. Calculate:

- (a) the voltage across the secondary coil
- (b) the current in the secondary coil
- (c) the average power delivered to the output circuit

[3 marks]

Solution:

Concept:

- For an ideal transformer, $V_s/V_p = N_s/N_p$, where N_p, N_s are the primary and secondary turns and V_p, V_s are their rms voltages.
- An ideal transformer has no power loss. Its current ratio is the inverse of its turns ratio: $I_s/I_p = N_p/N_s$. In the usual unity-power-factor treatment of this question, $P_{\text{out}} = P_{\text{in}} = V_p I_p = V_s I_s$.

Step 1: (a) Determine the secondary voltage The given quantities are $N_p = 650$, $N_s = 25$, $V_p = 240$ V and $I_p = 1.5$ A. Applying the ideal voltage ratio gives

$$V_s = V_p \frac{N_s}{N_p} = 240 \times \frac{25}{650} = \frac{120}{13} \text{ V} \approx 9.23 \text{ V}.$$

The secondary has fewer turns, so its voltage is lower, consistent with the stated step-down action.

Step 2: (b) Determine the secondary current Conservation of power in the ideal transformer gives the inverse current ratio. Therefore

$$I_s = I_p \frac{N_p}{N_s} = 1.5 \times \frac{650}{25} = 1.5 \times 26 = 39 \text{ A}.$$

Although the secondary voltage falls by a factor of 26, its current increases by the same factor. This current increase does not imply any creation of energy.

Step 3: (c) Calculate the average output power Using the standard unity-power-factor assumption implicit in the numerical problem, the average input power equals the product of the rms primary voltage and current. With no losses,

$$P_{\text{out}} = P_{\text{in}} = V_p I_p = 240 \times 1.5 = 360 \text{ W}.$$

A consistency check using the unrounded secondary voltage gives $V_s I_s = (120/13) \times 39 = 360$ W. More generally, a load with power factor $\cos \phi$ receives average power $360 \cos \phi$ W; the quoted 360 W is the intended result when that factor is unity.

Step 4: Conclusion (a) $V_s \approx 9.23$ V; (b) $I_s = 39$ A; (c) $P_{\text{out}} = 360$ W, under the standard unity-power-factor assumption.

Quick Tip to Solve: A step-down transformer reduces voltage and increases current in inverse ratios; multiply the unrounded secondary values to check conservation of power.

29(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]

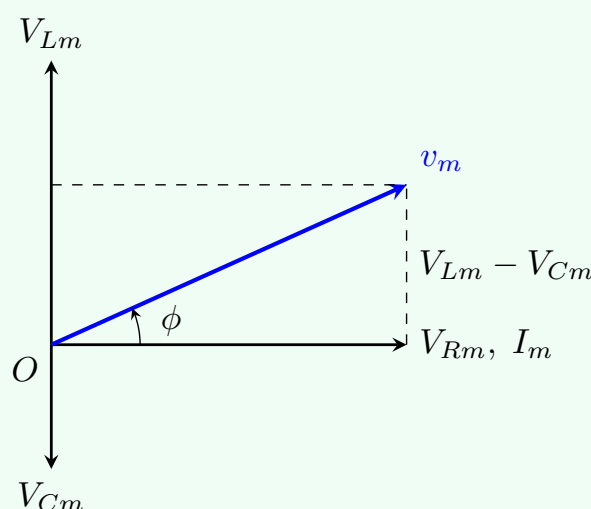
Solution:

Concept:

- Resistance R is the dissipative opposition to current. Impedance Z is the total opposition to alternating current, combining resistance and reactance; both are measured in ohms.
- In a series circuit the same current flows through all components. The reactances are $X_L = \omega L$ and $X_C = 1/(\omega C)$, where L is inductance, C is capacitance and ω is angular frequency.

Step 1: Distinguish resistance from impedance An ideal resistor dissipates energy as heat and its voltage is in phase with current. Its resistance is independent of frequency when temperature is fixed. Impedance also includes the opposition caused by the inductor and capacitor, which store and return energy. Hence impedance generally depends on frequency and may produce a phase difference between the source voltage and current. For a purely resistive circuit, $Z = R$.

Step 2: Construct the voltage phasors Take current amplitude I_m as the horizontal reference. The resistor voltage $V_{Rm} = I_m R$ is along current. The inductor voltage $V_{Lm} = I_m X_L$ leads current by 90° , while the capacitor voltage $V_{Cm} = I_m X_C$ lags by 90° . Their opposite vertical phasors leave the net reactive voltage $V_{Lm} - V_{Cm}$. The diagram illustrates $X_L > X_C$; for $X_C > X_L$, the resultant lies below the current axis.



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

Step 3: Obtain the impedance by vector addition The resistive and net reactive voltages are perpendicular. Applying Pythagoras to their resultant, whose amplitude is the given source amplitude v_m , gives

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

Since $Z = v_m/I_m$, this directly gives the impedance magnitude. Also $\tan \phi = (X_L - X_C)/R$, so for

the specified voltage $v = v_m \sin \omega t$, the current is $i = I_m \sin(\omega t - \phi)$.

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

Quick Tip to Solve: Draw the current and resistor voltage horizontally; subtract the opposing inductor and capacitor phasors before applying Pythagoras.

OR

29(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:

- For a series LCR circuit driven at angular frequency ω , the impedance is $Z = \sqrt{R^2 + (\omega L - 1/\omega C)^2}$, where R, L, C are resistance, inductance and capacitance.
- At fixed source amplitude v_m , the current amplitude is $I_m = v_m/Z$. Resonance occurs when the impedance is minimum and the current amplitude is maximum.

Step 1: Set the net reactance to zero Since R is fixed, the least possible impedance occurs when the nonnegative term $(\omega L - 1/\omega C)^2$ vanishes. Therefore the inductive and capacitive reactances must be equal:

$$\omega_0 L = \frac{1}{\omega_0 C} \implies \omega_0^2 = \frac{1}{LC}.$$

At resonance, $Z = R$, the source voltage and current are in phase, and $I_{m,\max} = v_m/R$. The individual inductor and capacitor voltages are opposite in phase and cancel in the phasor sum.

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

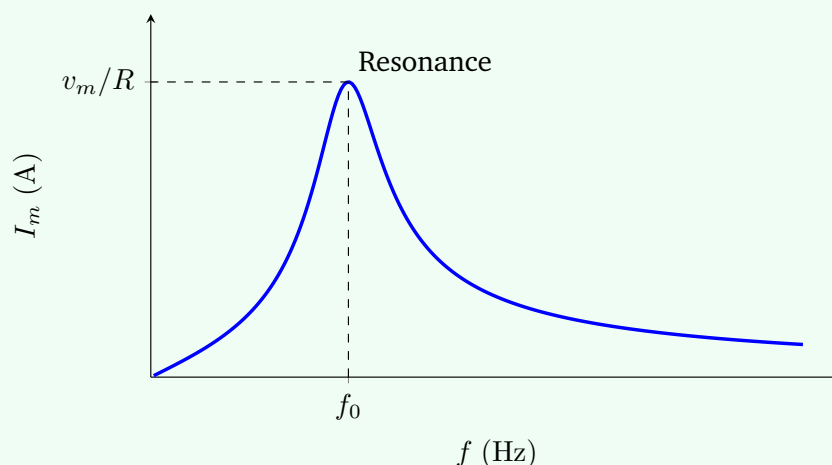
$$f_0 = \frac{1}{2\pi\sqrt{LC}}.$$

Thus the resonant frequency depends only on inductance L and capacitance C in the ideal series circuit. Increasing either one lowers f_0 . Resistance does not change this frequency, but it changes the peak current and the sharpness of the resonance curve.

Step 3: Draw the current versus frequency curve At low frequency, the capacitive reactance is large and the current is small. Increasing frequency reduces the net reactance until the current reaches its peak at f_0 . Above resonance, inductive reactance dominates and current falls again. For fixed source amplitude, the graph follows

$$I_m(f) = \frac{v_m}{\sqrt{R^2 + \left(2\pi fL - \frac{1}{2\pi fC}\right)^2}}.$$

The curve approaches zero as f tends to zero or becomes very large; it never becomes negative. A smaller resistance produces a taller, narrower resonance peak.



Current amplitude versus frequency for a fixed source amplitude.

Step 4: Conclusion Resonance requires $X_L = X_C$, giving $\omega_0 = 1/\sqrt{LC}$ and $f_0 = 1/(2\pi\sqrt{LC})$. The current has its maximum v_m/R at this frequency, which depends on L and C .

Quick Tip to Solve: For series resonance, first equate the two reactances; label the graph's peak at f_0 and its height at v_m/R .

30. A $100\ \mu\text{F}$ capacitor is charged by a $12\ \text{V}$ battery.

(a) How much electrostatic energy is stored by the capacitor?

(b) The capacitor is disconnected from the battery and connected in parallel to another uncharged $100\ \mu\text{F}$ capacitor. What is the electrostatic energy stored by the system? [3 marks]

Solution:

Concept:

- A capacitor of capacitance C , charged to potential difference V , stores electrostatic energy $U = \frac{1}{2}CV^2$ and charge $Q = CV$.
- When an isolated charged capacitor is joined in parallel to an uncharged capacitor, charge is redistributed until both have the same voltage. Total charge is conserved and parallel capacitances add.

Step 1: Calculate the initial stored energy for part (a) Convert the capacitance to farads before substituting. Here $C_1 = 100 \times 10^{-6}\ \text{F} = 1.00 \times 10^{-4}\ \text{F}$ and $V_1 = 12\ \text{V}$. Therefore

$$U_i = \frac{1}{2}C_1V_1^2 = \frac{1}{2}(100 \times 10^{-6})(12)^2 = 7.2 \times 10^{-3}\ \text{J}.$$

The charge initially supplied by the battery is $Q_i = C_1V_1 = 1.2 \times 10^{-3}\ \text{C}$.

Step 2: Find the common voltage after connection for part (b) The battery has been disconnected, so it cannot supply additional charge during redistribution. The second capacitor has $C_2 = 100\ \mu\text{F}$ and zero initial charge. The final equivalent capacitance is

$$C_{\text{eq}} = C_1 + C_2 = 200 \times 10^{-6}\ \text{F}.$$

Conservation of charge on the connected plates gives

$$V_f = \frac{Q_i}{C_1 + C_2} = \frac{1.2 \times 10^{-3}}{200 \times 10^{-6}} = 6 \text{ V.}$$

Thus each identical capacitor finally carries $600 \mu\text{C}$, and the common voltage is half its initial value.

Step 3: Calculate the final energy of both capacitors Both capacitors store energy at the common voltage, so the system's total stored energy is

$$\begin{aligned} U_f &= \frac{1}{2}(C_1 + C_2)V_f^2 \\ &= \frac{1}{2}(200 \times 10^{-6})(6)^2 \\ &= 3.6 \times 10^{-3} \text{ J.} \end{aligned}$$

Each capacitor stores $1.8 \times 10^{-3} \text{ J}$. Electrostatic energy is not conserved during charge redistribution: the missing $3.6 \times 10^{-3} \text{ J}$ is dissipated in the connecting circuit and may be radiated during the transient, while total energy remains conserved.

Step 4: Conclusion (a) The initially stored energy is $7.2 \times 10^{-3} \text{ J}$. (b) After connection, the total electrostatic energy of the two-capacitor system is $3.6 \times 10^{-3} \text{ J}$.

Quick Tip to Solve: For equal capacitors with the battery removed, the capacitance doubles and voltage halves; hence the total stored energy halves.

Section D (15 marks)

- 31(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 magnetic field of a current element: $d\vec{B} = \frac{\mu_0}{4\pi} \frac{I d\vec{\ell} \times \hat{r}}{r^2}$, where $d\vec{\ell}$ points along conventional current and $\hat{r}$ points from the element to the observation point.
- The magnetic fields from all elements of a circular loop add along its axis at the centre; their direction follows the right-hand thumb rule.
- A charge of magnitude e completing one revolution in time T constitutes a current of magnitude $I = e/T$. For uniform circular motion, $T = 2\pi r/v$.

Step 1: (i) State Biot-Savart's law The field contribution is directly proportional to the current I , the element length $d\ell$, and $\sin \theta$, and inversely proportional to the square of the separation r . Here θ is the angle between $d\vec{\ell}$ and $\vec{r}$. In vacuum,

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

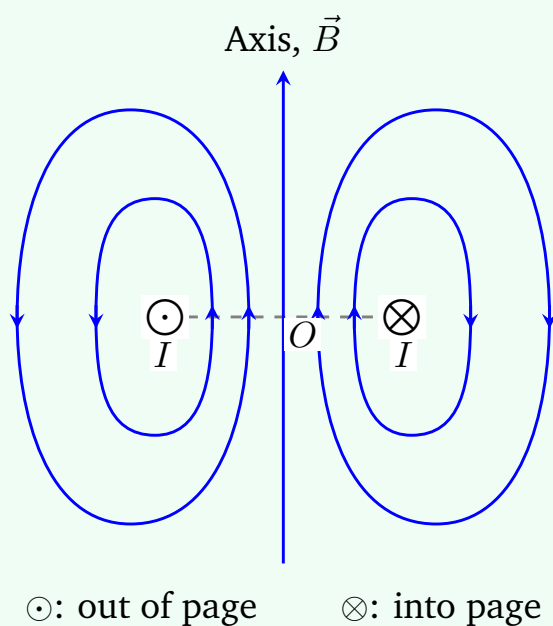
The direction of $d\vec{B}$ is perpendicular to the plane containing $d\vec{\ell}$ and $\vec{r}$, along their vector product.

Step 2: Integrate the field around the circular loop For every element of a loop of radius a , the centre is at distance a . The current element is tangential and the vector from the element to the centre is radial, so $\theta = 90^\circ$. Every contribution is normal to the loop in the same direction, so their magnitudes add:

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

Curl the fingers of the right hand along the current: the thumb gives the axial field direction. Viewed from the face where the current is anticlockwise, the field emerges towards the observer.

Step 3: Show the magnetic field lines and their direction The diagram is a section through the loop's axis: the circular wire cuts the page at the two marked points. The symbols $\odot$ and $\otimes$ denote conventional current out of and into the page, respectively. With these current directions, the field is upward through the interior of the loop and returns downward outside. The field lines form closed curves and never intersect. Close to the centre, they are nearly straight and parallel to the axis.



Magnetic field lines in an axial section of the current loop; the two symbols are wire cross-sections.

Step 4: (ii) Find the period and the equivalent current One electron of charge magnitude $e = 1.6 \times 10^{-19} \text{ C}$ passes any chosen point of the orbit once every revolution. With $r = 10^{-10} \text{ m}$ and $v = 10^7 \text{ m s}^{-1}$,

$$\begin{aligned} T &= \frac{2\pi r}{v} = \frac{2\pi \times 10^{-10}}{10^7} = 2\pi \times 10^{-17} \text{ s}, \\ I &= \frac{e}{T} = \frac{ev}{2\pi r} \\ &= \frac{1.6 \times 10^{-19} \times 10^7}{2\pi \times 10^{-10}} = 2.55 \times 10^{-3} \text{ A}. \end{aligned}$$

The electron is negatively charged, so the conventional current is opposite to the direction in which the electron revolves.

Step 5: Conclusion The magnetic field at the centre of the single circular loop is $B = \mu_0 I / (2a)$, normal to its plane with the direction given by the right-hand rule. The orbiting electron constitutes a current of magnitude $2.55 \times 10^{-3} \text{ A} = 2.55 \text{ mA}$, opposite to its motion.

Quick Tip to Solve: At the loop centre, use $r = a$, $\sin \theta = 1$ and $\oint dl = 2\pi a$. For an orbiting charge, divide its charge by the revolution period, not by the speed.

OR

31(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 charge q moving with drift velocity $\vec{v}_d$ in a uniform magnetic field $\vec{B}$ experiences $\vec{f} = q\vec{v}_d \times \vec{B}$.
- For a straight conductor of length l , cross-sectional area A , and carrier number density n , the number of carriers is $N = nAl$. The conventional current density is $\vec{J} = nq\vec{v}_d$.
- The field at distance r from a long straight wire carrying current I_A is $B_A = \mu_0 I_A / (2\pi r)$. Opposite parallel currents repel.

Step 1: (i) Derive the force on the conductor Consider the length l of the conductor lying in the uniform field. Summing the magnetic forces on its $N = nAl$ mobile charge carriers gives

$$\vec{F} = Nq\vec{v}_d \times \vec{B} = Al\vec{J} \times \vec{B}.$$

Since $JA = I$, define $\vec{l}$ to have magnitude l and point along conventional current. Then

$$\vec{F} = I\vec{l} \times \vec{B}, \quad F = IlB \sin \theta,$$

where θ is the angle between the current and the magnetic field. For electrons both the charge and drift direction are opposite to the corresponding positive-charge convention; $\vec{J}$ still points along conventional current. The forces on the carriers are transmitted to the conductor.

Step 2: (i) State the direction rule and the extreme values Use Fleming's left-hand rule: hold the thumb, forefinger and middle finger of the left hand mutually perpendicular. The forefinger indicates the magnetic field, the middle finger the conventional current, and the thumb the force on the conductor. For fixed I , l , and B , the force is maximum when $\theta = 90^\circ$, so $F_{\max} = IlB$. It is minimum, equal to zero, when $\theta = 0^\circ$ or 180° , that is, when the conductor is parallel or antiparallel to the field.

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

$$r = 2.5 \times 10^{-2} \text{ m}, \quad l = 0.10 \text{ m}, \quad I_A = 5.0 \text{ A}, \quad I_B = 2.5 \text{ A}.$$

Treating air as vacuum for magnetic permeability,

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

The magnetic field of wire A is perpendicular to wire B.

Step 4: (ii) Apply the conductor-force formula With $\theta = 90^\circ$, the force on the stated length of B is

$$F = I_B l B_A = (2.5)(0.10)(4.0 \times 10^{-5}) = 1.0 \times 10^{-5} \text{ N.}$$

Equivalently, $F = \mu_0 I_A I_B l / (2\pi r)$. The currents flow in opposite directions, so the force pushes B away from A. This is the force on the specified length, not the force per unit length.

Step 5: Conclusion $\vec{F} = I\vec{l} \times \vec{B}$, directed by Fleming's left-hand rule. The maximum is IlB for a perpendicular conductor and the minimum is zero for a parallel conductor. The force exerted by A on 10 cm of B is $1.0 \times 10^{-5} \text{ N}$, repulsive.

Quick Tip to Solve: Convert both the separation and the chosen wire length from centimetres to metres before using $F = \mu_0 I_A I_B l / (2\pi r)$; opposite currents repel.

32(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:

- Interference involves superposition of coherent waves from distinct sources; single-slit diffraction involves superposition of secondary wavelets from different parts of the same aperture.
- In Young's double-slit experiment, maxima satisfy $d \sin \theta = m\lambda$. Here d is slit separation, λ is wavelength and m is the fringe order.
- In the small-angle limit the linear fringe width is $\beta = \lambda D/d$, where D is the slit-to-screen distance. The angular fringe width is λ/d .

Step 1: (i)(1) Compare the widths in the two patterns In the usual small-angle Young's interference pattern, successive bright fringes are equally spaced; bright and dark bands have equal widths. In a single-slit diffraction pattern, the central bright maximum extends between the first minima on either side and is approximately twice as wide as each secondary bright band. Thus the diffraction pattern does not have the same uniform bright-band width as the ideal interference pattern.

Step 2: (i)(1) Compare the intensities in the two patterns For two coherent interfering sources of equal intensity and ideal narrow slits, all interference maxima have the same intensity. In single-slit diffraction the central maximum is the brightest, and the intensities of successive secondary maxima decrease as one moves away from the centre. These are two standard distinctions: fringe widths and maximum intensities. The equal-intensity statement for interference refers to the ideal two-source pattern, ignoring the finite slit diffraction envelope.

Step 3: (i)(2) Name the factors controlling fringe width From $\beta = \lambda D/d$, two factors are the wavelength λ and the slit-to-screen distance D : increasing either increases the fringe width in direct proportion when the other quantities are fixed. The slit separation d also affects the width inversely; increasing the separation makes the fringes closer together. The first two factors already meet the requested number.

Step 4: (ii)(1) Find the angular separation The central maximum has order $m = 0$ at $\theta = 0$. Its adjacent maximum has $m = 1$, so the path difference there is one wavelength. Using the given $d = 100\lambda$,

$$\sin \theta_1 = \frac{\lambda}{d} = \frac{1}{100} = 0.01.$$

Since this is a small angle, $\sin \theta_1 \simeq \theta_1$ in radians, giving

$$\Delta\theta \simeq \frac{\lambda}{d} = 1.0 \times 10^{-2} \text{ rad.}$$

The exact expression is $\theta_1 = \sin^{-1}(0.01)$, which agrees with this result to the stated precision. The wavelength cancels because the separation was specified as a multiple of it.

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

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

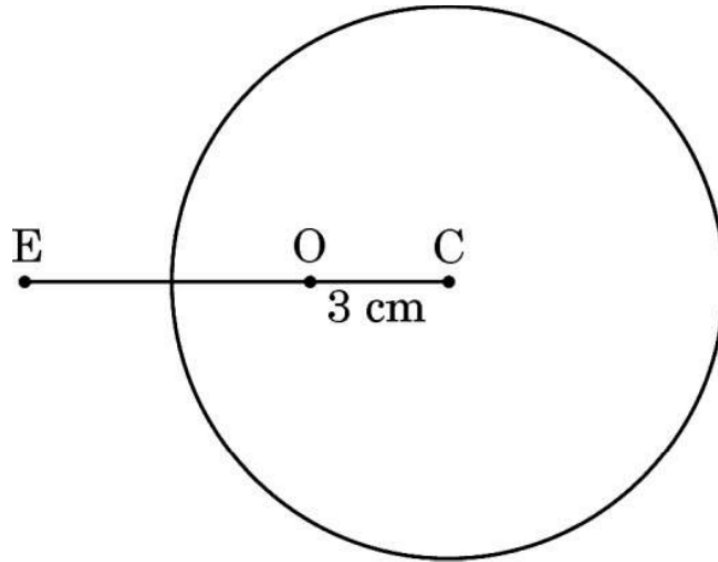
This also follows from $\Delta y = D \tan \theta_1 \simeq D\theta_1$. The two adjacent maxima on opposite sides of the centre would be separated by twice this distance, but the question asks for the centre-to-adjacent distance.

Step 6: Conclusion Ideal interference fringes have uniform widths and equal maximum intensities; single-slit diffraction has a central maximum of twice the secondary-band width and decreasing secondary intensities. Fringe width depends on wavelength and screen distance (also inversely on slit separation). The requested separations are $\Delta\theta = 0.010 \text{ rad}$ and $\Delta y = 5.0 \text{ mm}$, in the usual small-angle approximation.

Quick Tip to Solve: When d is given as a multiple of λ , cancel λ first. Centre to adjacent maximum is one fringe width, not two.

32(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:

- Refraction at a spherical surface follows Snell's law, $n_1 \sin i = n_2 \sin r$. For paraxial rays, all angles are small in radians, so $n_1 i = n_2 r$.
- In the Cartesian sign convention, distances are measured from the pole P , positive along the incident light. Thus u , v and R are signed object, image and centre-of-curvature distances.
- A virtual image has $v < 0$ when it lies on the incident side of the refracting surface; this image gives the apparent position of an embedded object.

Step 1: (i) Set up the paraxial ray geometry Consider a convex spherical surface with its centre C on the transmitted side. Put the axial object O to the left of the pole P , and consider a ray striking the surface at A , a small height h above the principal axis. The normal at A is AC . For a real image I on the right, let α , β and γ be the small positive angles made by OA , AI and AC , respectively, with the axis. Geometry gives

$$i = \alpha + \gamma, \quad r = \gamma - \beta.$$

Snell's law in the small-angle approximation therefore gives

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

Rearranging before substituting distances,

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

Step 2: (i) Express the angles using signed distances To paraxial accuracy, the axial displacement of A from P is negligible. If $U = OP$ and $V = PI$ are positive magnitudes in the chosen geometry, then

$$\alpha \simeq \frac{h}{U}, \quad \beta \simeq \frac{h}{V}, \quad \gamma \simeq \frac{h}{R}.$$

Substitution and cancellation of h give

$$\frac{n_1}{U} + \frac{n_2}{V} = \frac{n_2 - n_1}{R}.$$

Here the Cartesian distances are $u = -U$, $v = V$, and $R > 0$. Thus the spherical refraction relation is

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

With Cartesian signs assigned consistently, the same relation applies to concave surfaces and virtual images as well.

Step 3: (ii) Assign signs at the surface facing the observer The printed figure places bubble O between the centre C and the observer E . The light travels from the bubble towards the left surface and then into air, so take leftwards as the positive direction. The bubble is $6.0 - 3.0 = 3.0$ cm inside that surface. Both the bubble and the centre are on its negative side. Hence

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

Only this glass-to-air surface refracts the rays reaching E ; the opposite surface is not in their path.

Step 4: (ii) Calculate the image position Using centimetres throughout in the spherical refraction relation,

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

The negative sign locates a virtual image within the glass, on the same side of the surface as the bubble. Its distance from the centre towards E is $6.0 - 2.4 = 3.6$ cm.

Step 5: Conclusion (i) The required relation is $\frac{n_2}{v} - \frac{n_1}{u} = \frac{n_2 - n_1}{R}$. (ii) The bubble appears 2.4 cm beneath the surface facing E , or 3.6 cm from C towards E ; its image is virtual.

Quick Tip to Solve: Measure the bubble's depth from the observed surface first, then set the positive direction along its outgoing light. Here both u and R are negative even though the sphere's radius has magnitude 6.0 cm.

- 33(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 describes the electrostatic force between stationary point charges. In vacuum, its magnitude is $F = k|q_1 q_2|/r^2$, where $k = 1/(4\pi\epsilon_0)$, r is their separation and ϵ_0 is the permittivity of free space.
- Electric flux through an element is $d\Phi = \vec{E} \cdot d\vec{S}$. Gauss's law states that total outward flux through a closed surface is $Q_{\text{enclosed}}/\epsilon_0$.
- A displacement vector divided by its magnitude gives the corresponding unit vector. The force vector equals the force magnitude times its direction unit vector.

Step 1: (i) State Coulomb's law and write its vector form The magnitude of the electrostatic force between two stationary point charges is directly proportional to the product of the magnitudes of their charges and inversely proportional to the square of their separation. The force acts along the line joining the charges: like charges repel and unlike charges attract. Let charges q_1 and q_2 be at position vectors $\vec{r}_1$ and $\vec{r}_2$. Define $\vec{r}_{21} = \vec{r}_2 - \vec{r}_1$, $r_{21} = |\vec{r}_{21}|$, and $\hat{r}_{21} = \vec{r}_{21}/r_{21}$. The force on charge 2 due to charge 1 in vacuum is

$$\vec{F}_{2 \leftarrow 1} = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r_{21}^2} \hat{r}_{21} = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2 \vec{r}_{21}}{r_{21}^3}.$$

Signed charges in this expression automatically give repulsion or attraction. The force on charge 1 is equal and opposite.

Step 2: (ii) Relate the inverse-square law to spherical flux Surround a point charge Q by a concentric spherical Gaussian surface of radius r . Coulomb's law gives a radial field $\vec{E} = kQ\hat{r}/r^2$, while the outward surface area is $4\pi r^2$. Hence

$$\Phi = \oint \vec{E} \cdot d\vec{S} = \frac{Q}{4\pi\epsilon_0 r^2} (4\pi r^2) = \frac{Q}{\epsilon_0}.$$

The factor r^2 in area exactly cancels the inverse-square dependence of the field. Consequently, the flux depends on the enclosed charge and is independent of the sphere's radius. If the field instead varied as r^{-p} , this spherical flux would vary as r^{2-p} ; it is independent of radius precisely for $p = 2$.

Step 3: (ii) Extend the flux argument to a closed surface For any small surface element viewed from Q , its signed solid angle is $d\Omega = (\hat{r} \cdot d\vec{S})/r^2$. The inverse-square field therefore gives $d\Phi = Q d\Omega/(4\pi\epsilon_0)$. A closed surface enclosing the charge subtends total solid angle 4π , so its flux is again Q/ϵ_0 . For an external charge the net signed solid angle is zero, giving zero net flux. Superposition for many charges yields

$$\oint \vec{E} \cdot d\vec{S} = \frac{Q_{\text{enclosed}}}{\epsilon_0}.$$

This explains how the distance dependence in Coulomb's law leads to Gauss's law for arbitrary closed surfaces, not only spheres.

Step 4: (iii) Determine the separation and direction from A to B Taking $a > 0$, the displacement from

$A(0, 0)$ to $B(a, a)$ is

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

Since the charges are q and $2q$, their product is $2q^2 > 0$ for nonzero q . The force on B points away from A , along this unit vector.

Step 5: (iii) Substitute into the vector force law Substitution of the charge product and the squared separation gives

$$\begin{aligned}\vec{F}_{B \leftarrow A} &= \frac{1}{4\pi\epsilon_0} \frac{2q^2}{(\sqrt{2}a)^2} \frac{\hat{i} + \hat{j}}{\sqrt{2}} \\ &= \frac{q^2}{4\pi\epsilon_0\sqrt{2}a^2} (\hat{i} + \hat{j}).\end{aligned}$$

The equal positive Cartesian components place the force at 45° above the positive x -axis. Its magnitude is $q^2/(4\pi\epsilon_0 a^2)$, consistent with using separation $\sqrt{2}a$ in the scalar law.

Step 6: Conclusion Coulomb's force is $\vec{F}_{2 \leftarrow 1} = q_1 q_2 \hat{r}_{21} / (4\pi\epsilon_0 r_{21}^2)$. Its inverse-square dependence makes closed-surface flux equal to $Q_{\text{enclosed}}/\epsilon_0$. 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 is directed from A towards B , with magnitude $q^2/(4\pi\epsilon_0 a^2)$ in SI force units when q and a are in coulombs and metres.

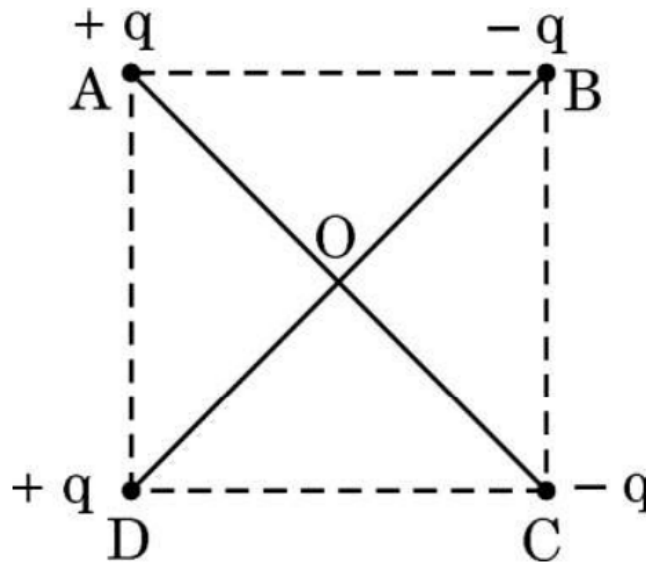
Quick Tip to Solve: Use the full diagonal separation $\sqrt{2}a$ in Coulomb's law, then multiply by the unit vector $(\hat{i} + \hat{j})/\sqrt{2}$. The vector $\hat{i} + \hat{j}$ alone is not a unit vector.

33(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:

- An electric dipole has charges $-q$ and $+q$, separated by $2a$. Its dipole moment is $\vec{p} = 2qa \hat{p}$, directed from the negative to the positive charge.
- Coulomb's field has magnitude kq/R^2 , where $k = 1/(4\pi\epsilon_0)$ and R is the charge-to-observation-point distance. Electric fields add as vectors.
- On the equatorial plane, components perpendicular to the dipole axis cancel; components opposite to $\vec{p}$ add. The distant-dipole approximation requires $r \gg a$.

Step 1: (i) Resolve the fields at an equatorial point Put $-q$ at $(-a, 0)$, $+q$ at $(a, 0)$, and take an equatorial point $P = (0, r)$. Each charge is a distance $R = \sqrt{r^2 + a^2}$ from P . The fields due to the two charges are

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

Their $\hat{j}$ components cancel, while both $\hat{i}$ components point towards the negative charge. Thus

$$\vec{E}_{\text{eq}} = -\frac{2kqa\hat{i}}{(r^2 + a^2)^{3/2}} = -\frac{1}{4\pi\epsilon_0} \frac{\vec{p}}{(r^2 + a^2)^{3/2}}.$$

Rotational symmetry about the dipole axis makes this expression valid at any point in its equatorial plane at distance r from its centre. For $r \gg a$, neglect a^2 against r^2 to obtain $\vec{E}_{\text{eq}} \simeq -k\vec{p}/r^3$.

Step 2: (ii) Compare fields at the two distances For a far-off point, the magnitude varies as $1/r^3$. On

changing the distance from r to $r/2$,

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

This uses the stated distant-point approximation, so the new distance also remains large compared with the dipole separation. The field direction stays opposite to the dipole moment.

Step 3: (iii) Add the four charge fields at the square's centre From the printed figure, A, D carry $+q$ and B, C carry $-q$. The side is $s = \sqrt{2} \text{ m}$, so each diagonal is $s\sqrt{2} = 2 \text{ m}$, and each vertex is 1 m from O . Each individual field therefore has magnitude

$$E_0 = \frac{kq}{(1 \text{ m})^2}.$$

At O , the fields from A and C both point along AC , towards C ; together their magnitude is $2E_0$. Those from D and B both point along DB , towards B , again with magnitude $2E_0$. These diagonal directions are perpendicular. Equivalently, their vertical components cancel and all four horizontal components point right. Hence

$$E_{\text{net}} = \sqrt{(2E_0)^2 + (2E_0)^2} = 2\sqrt{2}E_0 = \frac{2\sqrt{2}kq}{(1 \text{ m})^2}.$$

The direction is parallel to AB , from the midpoint of AD towards the midpoint of BC . The centre lies between each dipole's charges; the far-field equatorial formula cannot be substituted at O .

Step 4: Conclusion (i) $\vec{E}_{\text{eq}} = -\frac{\vec{p}}{4\pi\epsilon_0(r^2 + a^2)^{3/2}}$, opposite to $\vec{p}$. (ii) Halving a far-off equatorial distance increases the field eightfold. (iii) $E_{\text{net}} = \frac{2\sqrt{2}kq}{(1 \text{ m})^2}$, directed parallel to AB from AD towards BC .

Quick Tip to Solve: At the square's centre, mark each charge's field arrow before adding: all four horizontal components point towards the negative-charge side.

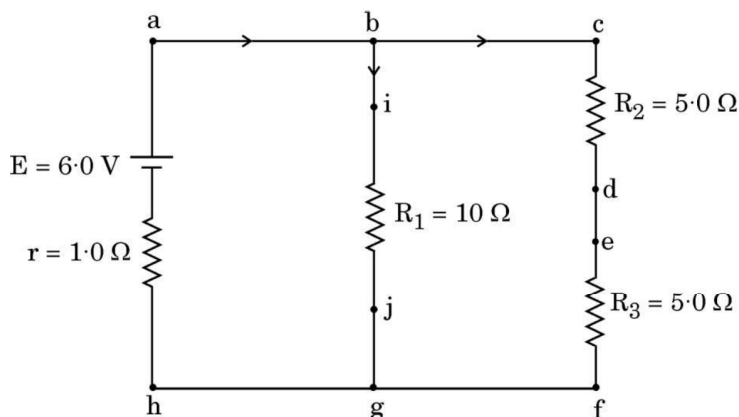
Section E (8 marks)

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]



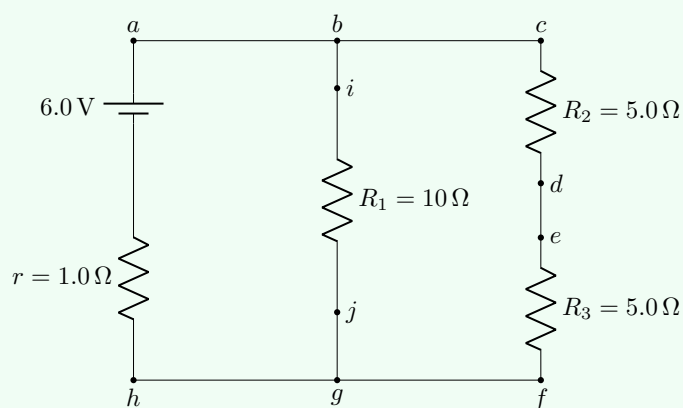
Solution:

Concept:

- An ideal connecting wire has negligible resistance, so its potential drop is $IR = 0$, even when it carries current.
- All labelled points connected by uninterrupted ideal wire belong to the same electrical node. A resistor or cell can separate different potentials.

Step 1: Trace the top and bottom conducting nodes Points a, b, c lie on the continuous top wire, and i connects directly to b above R_1 . Therefore $V_a = V_b = V_c = V_i$. On the bottom wire, h, g, f connect directly, and j connects to g below R_1 ; hence $V_h = V_g = V_f = V_j$.

Step 2: Identify the middle node on the right branch Points d and e are joined by wire between R_2 and R_3 , so $V_d = V_e$. They are not on the top or bottom node because a resistor intervenes in either direction. Similarly, i and j lie on opposite sides of R_1 , so the drawn vertical branch does not make them equipotential.



Circuit redrawn to show the three uninterrupted wire nodes.

Step 3: Conclusion The equal-potential groups are $\{a, b, c, i\}$, $\{h, g, f, j\}$, $\{d, e\}$.

Quick Tip to Solve: Trace each wire until a resistor or cell interrupts it; every labelled point reached before that interruption has the same potential.

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

[1 mark]

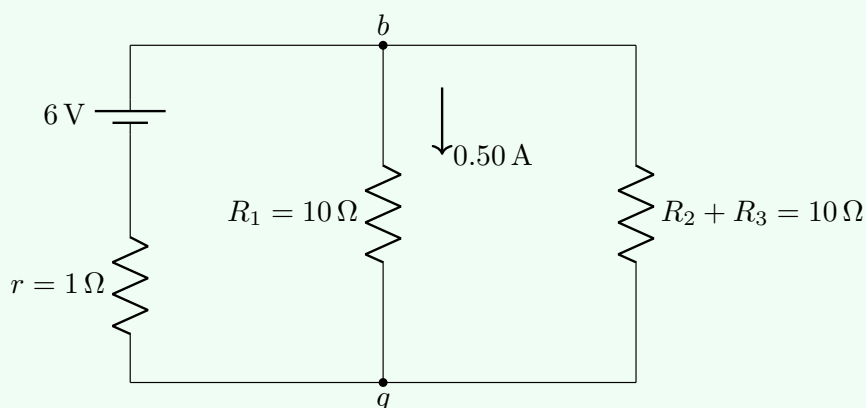
Solution:

Concept:

- Series resistances add, while two equal parallel resistances R have equivalent resistance $R/2$.
- The source current is $I = E/(R_{\text{ext}} + r)$, where E is the emf and r the cell's internal resistance. Equal parallel branches carry equal currents.

Step 1: Reduce the external circuit The right-hand arm has R_2 and R_3 in series, giving $5 + 5 = 10 \Omega$. It is in parallel with the 10Ω resistor R_1 in arm bg . Therefore

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



Equivalent circuit: both external branches have resistance 10Ω .

Step 2: Include internal resistance and divide the current The cell's 1Ω internal resistance is in series

with this parallel combination. Thus

$$I = \frac{6}{5 + 1} = 1 \text{ A}, \quad V_{bg} = IR_{\text{ext}} = 5 \text{ V}.$$

Each of the equal parallel branches carries half the source current. In particular, $I_{bg} = V_{bg}/R_1 = 5/10 \text{ A}$. The cell's positive terminal is connected to the upper wire, so conventional current travels from b down to g . Using $6/10$ would incorrectly treat the emf as the loaded terminal voltage.

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

Quick Tip to Solve: First combine the two right-arm resistors; the resulting equal parallel branches split the source current equally, after internal resistance is included.

34(c). Refer to the circuit diagram. Find the potential difference across resistance R_3 .

[2 marks]

Solution:

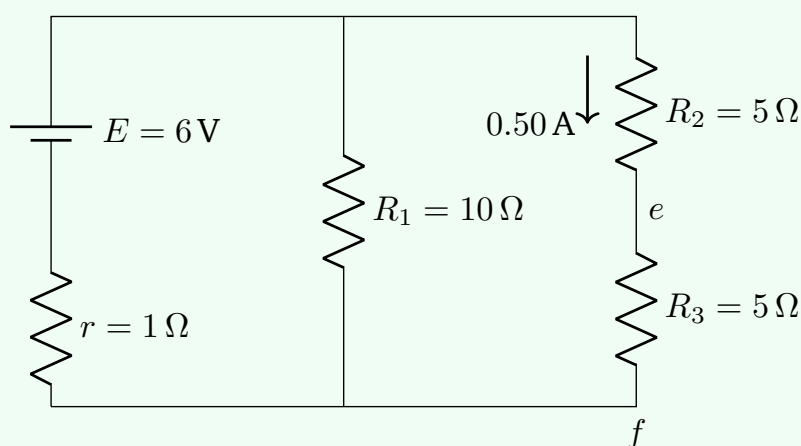
Concept:

- Series resistances add, whereas parallel branches have the same potential difference. The internal resistance r is in series with the entire external circuit.
- Ohm's law gives $I = E/(R_{\text{ext}} + r)$, where E is the cell emf and I is its total current; a resistor's voltage is its own branch current times its resistance.

Step 1: Reduce the external circuit The right-hand resistors carry the same current because no branch leaves their junction. Thus $R_2 + R_3 = 5 + 5 = 10 \Omega$. This combination is in parallel with $R_1 = 10 \Omega$:

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

The total resistance including the cell's internal resistance is $5 + 1 = 6 \Omega$.



The two external branches each have resistance 10Ω .

Step 2: Find the branch current and voltage drop The current supplied by the cell is

$$I = \frac{6.0}{6} = 1.0 \text{ A}.$$

The two external branches have equal resistance, so each carries 0.50 A . The terminal voltage is $E - Ir = 6 - 1 = 5 \text{ V}$; the emf itself is not the voltage across the external branches. Hence the drop

across the lower right-hand resistor is

$$V_{R_3} = I_{\text{right}} R_3 = 0.50 \times 5.0 = 2.5 \text{ V}.$$

Step 3: Conclusion The potential difference across R_3 is 2.5 V , with point e at a higher potential than point f .

Quick Tip to Solve: Include the internal resistance first; then divide the terminal voltage equally between the two equal series resistors on the right.

OR

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

[2 marks]

Solution:

Concept:

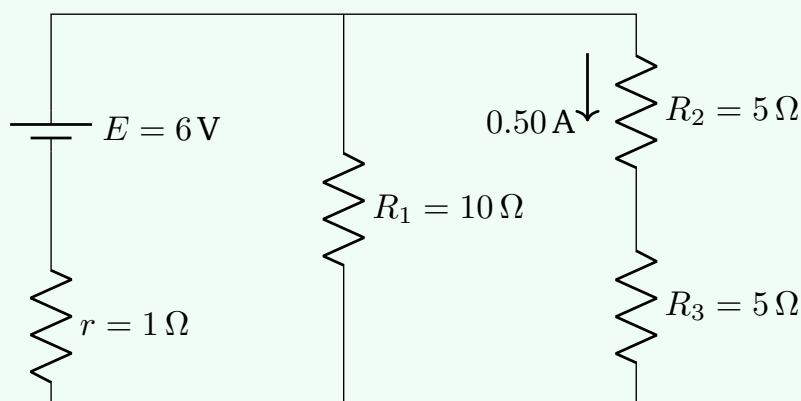
- The power converted to heat in a resistance is $P = I^2 R$, with I the current through that particular resistor, rather than the total cell current.
- Series resistances add; the equivalent resistance of two parallel resistors is $R_a R_b / (R_a + R_b)$. Internal resistance must be included when finding the total current.

Step 1: Calculate the current supplied by the cell The right-hand branch has the series combination $R_2 + R_3 = 5 + 5 = 10 \Omega$. It is in parallel with $R_1 = 10 \Omega$, giving

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

Adding the internal resistance $r = 1 \Omega$ gives a total of 6Ω . The cell therefore supplies

$$I = \frac{E}{R_{\text{ext}} + r} = \frac{6.0}{5 + 1} = 1.0 \text{ A}.$$



Equal external branch resistances divide the total current equally.

Step 2: Use the current in the right-hand branch The two external branches have equal resistance, so the total current divides equally. Thus $I_2 = I/2 = 0.50 \text{ A}$ flows through R_2 . Its voltage drop is $I_2 R_2 = 2.5 \text{ V}$. Therefore,

$$P_{R_2} = I_2^2 R_2 = (0.50)^2 \times 5.0 = 1.25 \text{ W}.$$

As a check, $P = VI = 2.5 \times 0.50 = 1.25 \text{ W}$ gives the same value.

Step 3: Conclusion The power dissipated in R_2 is 1.25 W .

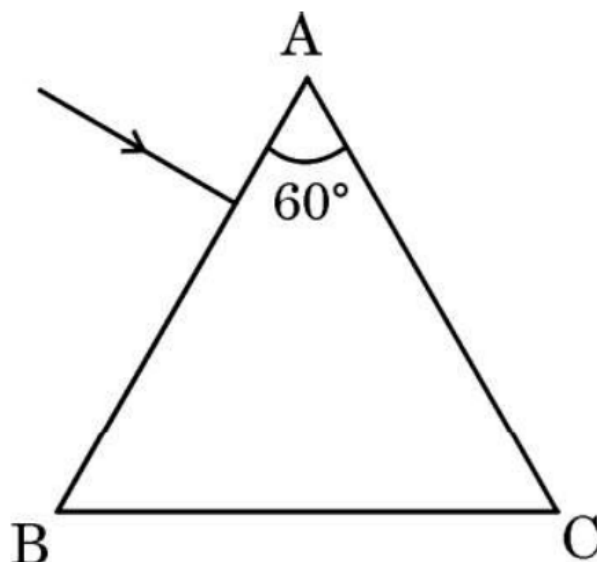
Quick Tip to Solve: Use the half-current in the right branch before squaring it; using the total cell current would overestimate this resistor's power fourfold.

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]



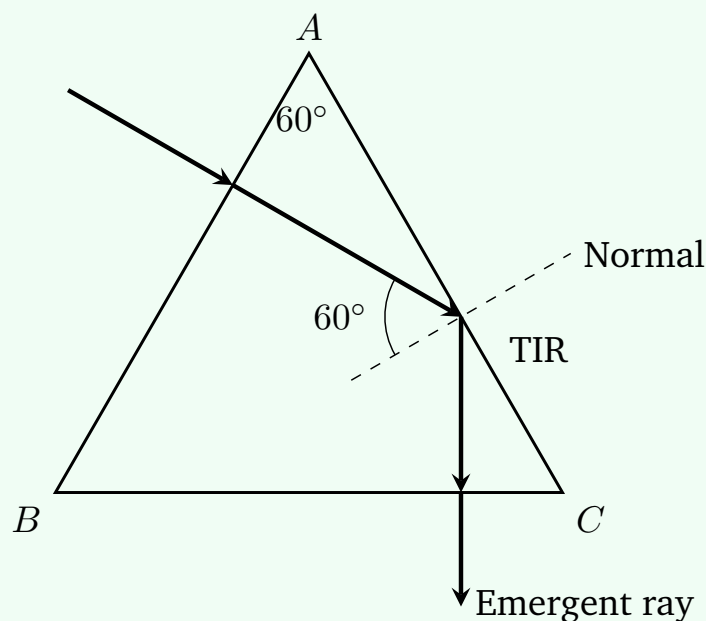
Solution:

Concept:

- Normal incidence causes no bending. Total internal reflection occurs for light going from an optically denser to a rarer medium when $i > i_c$, where i is measured from the normal.
- The angle of reflection equals the angle of incidence; the prism's equilateral geometry fixes the normals to its faces.

Step 1: Enter normally and reach the second face At AB , the incident ray follows the normal into the prism without deviation. At AC , the angle between this ray and the outward normal is 60° . Since $60^\circ > 24.5^\circ$, the ray undergoes total internal reflection at AC .

Step 2: Reflect towards the base and emerge Reflection at AC sends the ray vertically towards BC . It reaches the base normally and emerges into air without bending. The dashed line at the reflecting face in the diagram is the normal, not another ray.



Ray passage through the equilateral prism; total internal reflection occurs at AC.

Step 3: Conclusion The ray enters AB undeviated, is totally internally reflected at AC, and emerges normally through BC.

Quick Tip to Solve: Measure the angle at the second face from its normal: it is 60°, even though the ray makes 30° with the face.

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

Solution:

Concept:

- The absolute refractive index is $n = c/v$, where c is the speed of light in vacuum and v is its speed in the material.
- For a transparent medium with $n > 1$, the speed is smaller than c . The critical angle is not needed when the refractive index is already given.

Step 1: Rearrange the definition of refractive index The prism has refractive index $n = 2.41$. Using $n = c/v$, isolate the required speed:

$$v = \frac{c}{n}.$$

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

$$v = \frac{3.0 \times 10^8}{2.41} = 1.245 \times 10^8 \text{ m s}^{-1}.$$

Dividing by the dimensionless refractive index retains the speed unit and gives a value smaller than the vacuum speed, as expected.

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: Divide the vacuum speed by 2.41; multiplying would wrongly predict that light travels faster inside this prism than in vacuum.

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

[2 marks]

Solution:

Concept:

- Total internal reflection occurs when light travels from an optically denser to a rarer medium and strikes their boundary at an angle greater than the critical angle, measured from the normal.
- This process redirects light back into the denser medium. It is used to guide light in optical fibres and to obtain bright images with reflecting prisms.

Step 1: Explain light transmission through optical fibres An optical fibre has a transparent core surrounded by cladding of lower refractive index. Light entering within the allowed range of directions strikes the core–cladding boundary at an incidence angle greater than its critical angle. Repeated total internal reflections keep the light inside the core and guide it along the fibre, including gentle bends. This is used in optical communication and in medical endoscopes to carry light into, and images from, otherwise inaccessible regions.

Step 2: Explain the use of reflecting prisms In a right-angled glass prism, a ray entering normally through a suitable face can strike the hypotenuse at 45° . For ordinary glass in air this exceeds the critical angle of about 42° , so the ray undergoes total internal reflection and changes direction by 90° . Such prisms redirect light in periscopes and binoculars, producing bright images without a silvered reflecting surface.

Step 3: Conclusion Two applications are guiding light by repeated total internal reflection in optical fibres, and redirecting light with totally reflecting prisms in optical instruments.

Quick Tip to Solve: For each application, name the denser medium and the reflecting boundary, then explain how repeated or directed reflection serves the device.

OR

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

[2 marks]

Solution:

Concept:

- Total internal reflection is the complete reflection of incident light back into the optically denser medium at its boundary with an optically rarer medium, when the incidence angle exceeds the critical angle.
- The critical angle C is the angle of incidence in the denser medium for which the refracted ray grazes the boundary, so its angle of refraction is 90° . For refractive indices $n_1 > n_2$, $\sin C = n_2/n_1$.

Step 1: State the condition on the two media Light must travel from an optically denser medium towards an optically rarer medium, that is, from refractive index n_1 to n_2 , with $n_1 > n_2$. Only in this direction does refraction bend the ray away from the normal sufficiently to reach the grazing condition. Optical density here refers to refractive index, not mass density.

Step 2: State the condition on the incidence angle The angle of incidence i , measured between the incident ray and the normal in the denser medium, must be greater than the critical angle: $i > C$. At $i = C$, the refracted ray lies along the interface; this is the limiting condition, not total internal reflection. At $i > C$, Snell's law would require $\sin r > 1$, so no refracted ray propagates into the rarer medium and the light is reflected back.

Step 3: Conclusion Total internal reflection is complete reflection back into the denser medium. Its two necessary conditions are travel from an optically denser to a rarer medium and an angle of incidence greater than the critical angle.

Quick Tip to Solve: Always write both conditions: denser to rarer, and $i > C$; use a strict inequality because $i = C$ gives a grazing refracted ray.