

CBSE Class 12 Physics Question Paper 2025 with Solution PDF-Set 55/7/2



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 **33** questions. **All** questions are **compulsory**.
- (ii) This question paper is divided into **five** sections – **Sections A, B, C, D** and **E**.
- (iii) In **Section A** – Questions no. **1 to 16** are Multiple Choice type questions. Each question carries **1** mark.
- (iv) In **Section B** – Questions no. **17 to 21** are Very Short Answer type questions. Each question carries **2** marks.
- (v) In **Section C** – Questions no. **22 to 28** are Short Answer type questions. Each question carries **3** marks.
- (vi) In **Section D** – Questions no. **29 and 30** are case study-based questions. Each question carries **4** marks.
- (vii) In **Section E** – Questions no. **31 to 33** are Long Answer type questions. Each question carries **5** marks.
- (viii) There is no overall choice given in the question paper. However, an internal choice has been provided in few questions in all the Sections except Section A.
- (ix) Kindly note that there is a separate question paper for Visually Impaired candidates.
- (x) Use of calculators is not allowed.

You may use the following values of physical constants wherever necessary :

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

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

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

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

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

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

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

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

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

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

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

Section A (16 marks)

1. The electric field (E) and electric potential (V) at a point inside a charged hollow metallic sphere are respectively: [1 mark]

- (A) $E = 0, V = 0$
(B) $E = 0, V = V_0$ (a constant)
(C) $E \neq 0, V \neq 0$
(D) $E = E_0$ (a constant), $V = 0$

Correct Answer: (B) $E = 0, V = V_0$ (a constant)

Solution:

Concept:

- In electrostatic equilibrium, excess charge resides on the outer surface of an isolated hollow conductor, and the electric field in its empty cavity is zero.
- The potential difference is $V_2 - V_1 = - \int_1^2 \vec{E} \cdot d\vec{l}$; zero field means constant potential, not necessarily zero potential.

Step 1: Apply electrostatic shielding The charged metallic sphere is in electrostatic equilibrium. With no charge inside its cavity, the electric field at every interior point is $E = 0$. Thus the nonzero-field choices (C) and (D) are excluded.

Step 2: Determine the interior potential Since the field vanishes throughout the interior, there is no potential change from the surface to an interior point. The potential everywhere inside equals the surface value V_0 . With infinity as the reference, a sphere of charge Q and radius R has $V_0 = Q/(4\pi\epsilon_0 R)$; charging the sphere does not generally make this value zero. Hence option (A) incorrectly equates zero field with zero potential.

Step 3: Conclusion Inside the charged hollow metallic sphere, $E = 0$ and $V = V_0$, a constant. Hence, the correct option is (B).

Quick Tip to Solve: Use zero field to infer zero potential difference; then obtain the constant potential from the sphere's surface.

2. The dimensions of 'self-inductance' are: [1 mark]

- (A) $[MLT^{-2}A^{-2}]$
(B) $[ML^2T^{-1}A^{-1}]$
(C) $[ML^{-1}T^{-2}A^{-2}]$
(D) $[ML^2T^{-2}A^{-2}]$

Correct Answer: (D) $[ML^2T^{-2}A^{-2}]$

Solution:

Concept:

- An inductor stores magnetic energy $U = \frac{1}{2}LI^2$, where L is self-inductance and I is current.
- Energy has dimensions $[ML^2T^{-2}]$, while current has dimensions $[A]$. Numerical factors carry no dimensions.

Step 1: Isolate the inductance Rearranging the energy relation gives $L = 2U/I^2$. Thus the dimension

of inductance is the dimension of energy divided by that of current squared:

$$[L_{\text{inductance}}] = \frac{[ML^2T^{-2}]}{[A^2]} = [ML^2T^{-2}A^{-2}].$$

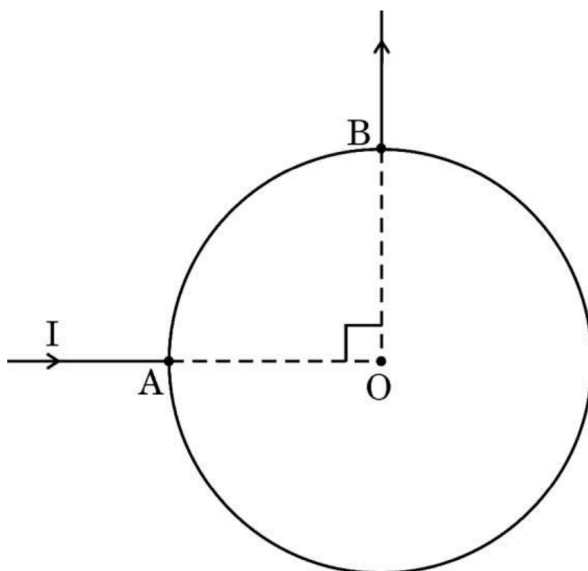
Here the L inside the dimension bracket denotes length, not inductance.

Step 2: Check the listed exponents Option (D) has the required length power 2, time power -2 , and current power -2 . Option (A) has length power 1, option (C) has length power -1 , and option (B) has incorrect time and current powers. None of these three can represent energy divided by current squared.

Step 3: Conclusion The dimensions of self-inductance are $[ML^2T^{-2}A^{-2}]$. Hence, the correct option is (D).

Quick Tip to Solve: Recover the dimensions of inductance quickly from magnetic energy divided by current squared, using $U = \frac{1}{2}LI^2$.

3. In a circular loop of radius R , current I enters at point A and exits at point B , as shown in the figure. The value of the magnetic field at the centre O of the loop is: [1 mark]



- (A) $\frac{\mu_0 I}{R}$
- (B) zero
- (C) $\frac{\mu_0 I}{2R}$
- (D) $\frac{\mu_0 I}{4R}$

Correct Answer: (B) zero

Solution:

Concept:

- For a uniform wire, resistance is proportional to length; current divides inversely in proportion to the resistances of parallel paths.
- A circular arc of radius R , current i , and angle θ in radians produces $B = \mu_0 i \theta / (4\pi R)$ at its centre,

with direction given by the right-hand rule.

Step 1: Divide the current between the arcs The figure shows a quarter-circle short arc from A to B and a three-quarter-circle long arc. Their resistances are in the ratio 1 : 3, so their currents are $3I/4$ and $I/4$, respectively. The short-arc current circulates clockwise about O, while the long-arc current circulates anticlockwise.

Step 2: Add the magnetic fields with their directions The two arc contributions have equal magnitudes:

$$B_{\text{short}} = \frac{\mu_0}{4\pi R} \frac{3I}{4} \frac{\pi}{2} = \frac{3\mu_0 I}{32R},$$
$$B_{\text{long}} = \frac{\mu_0}{4\pi R} \frac{I}{4} \frac{3\pi}{2} = \frac{3\mu_0 I}{32R}.$$

They point into and out of the page, so they cancel. The straight leads lie along radial lines through O and give zero field there because $d\vec{l} \times \vec{r} = 0$. Options (A), (C), and (D) retain a nonzero contribution and therefore miss this cancellation.

Step 3: Conclusion The net magnetic field at O is zero. Hence, the correct option is (B).

Quick Tip to Solve: For two uniform arcs between the same terminals, $i\theta$ is equal for both arcs; check their opposite senses before adding their fields.

4. The frequency of a photon of energy 1.326 eV is:

[1 mark]

- (A) 1.18×10^{14} Hz
- (B) 3.20×10^{14} Hz
- (C) 4.20×10^{15} Hz
- (D) 4.80×10^{15} Hz

Correct Answer: (B) 3.20×10^{14} Hz

Solution:

Concept:

- A photon has energy $E = h\nu$, where ν is its frequency and $h = 6.63 \times 10^{-34}$ J s is Planck's constant.
- To use h in SI units, convert energy with $1 \text{ eV} = 1.6 \times 10^{-19}$ J.

Step 1: Convert the photon energy The stated energy is in electron volts, not joules. Converting before substitution gives

$$E = 1.326 \times 1.6 \times 10^{-19} = 2.1216 \times 10^{-19} \text{ J}.$$

Step 2: Use the photon energy relation Dividing the energy by Planck's constant gives

$$\nu = \frac{E}{h} = \frac{2.1216 \times 10^{-19}}{6.63 \times 10^{-34}} = 3.20 \times 10^{14} \text{ Hz}.$$

The unit is J/(J s) = s^{-1} . Option (A) has the wrong numerical coefficient, while (C) and (D) have

both the wrong coefficient and a frequency an order of magnitude too large. Only option (B) agrees with the calculation.

Step 3: Conclusion The photon frequency is 3.20×10^{14} Hz. Hence, the correct option is (B).

Quick Tip to Solve: Convert eV to joules before dividing by h ; track the exponent $-19 - (-34) = 15$ and then normalize the coefficient.

5. A metal rod of length 50 cm is held vertically and moved with a velocity of 10 m/s towards east. The horizontal component of the Earth's magnetic field at the place is 0.4 G. The emf induced across the ends of the rod is: [1 mark]

- (A) 0.1 mV
- (B) 0.2 mV
- (C) 0.8 mV
- (D) 1.6 mV

Correct Answer: (B) 0.2 mV

Solution:

Concept:

- The motional emf in a straight rod is $\varepsilon = Blv$ when its length, its velocity, and the relevant magnetic field component are mutually perpendicular.
- Earth's horizontal magnetic field points northward. An eastward-moving vertical rod is perpendicular to both the velocity and this field; $1 \text{ G} = 10^{-4} \text{ T}$.

Step 1: Select the field and convert the units The horizontal field produces a vertical magnetic force on moving charges, separating charge between the rod ends. Any vertical field component produces a horizontal force and contributes no emf along this vertical rod. The required SI values are

$$B_H = 0.4 \times 10^{-4} = 4 \times 10^{-5} \text{ T}, \quad l = 0.50 \text{ m}, \quad v = 10 \text{ m s}^{-1}.$$

Step 2: Calculate the induced emf Since the relevant vectors are mutually perpendicular,

$$\varepsilon = B_H lv = (4 \times 10^{-5})(0.50)(10) = 2 \times 10^{-4} \text{ V} = 0.2 \text{ mV}.$$

This equals option (B). The values in (A), (C), and (D) differ by factors of two, four, and eight, respectively, from the product of the correctly converted quantities.

Step 3: Conclusion The magnitude of the induced emf is 0.2 mV. Hence, the correct option is (B).

Quick Tip to Solve: Use the horizontal Earth-field component for a vertical moving rod, and convert gauss to tesla before calculating Blv .

6. Germanium crystal is doped at room temperature with a minute quantity of boron. The charge carriers in the doped semiconductors will be: [1 mark]

- (A) electrons only
- (B) holes only
- (C) holes and few electrons
- (D) electrons and few holes

Correct Answer: (C) holes and few electrons

Solution:

Concept:

- Germanium is tetravalent, while boron is trivalent. A boron impurity acts as an acceptor and produces a p-type semiconductor.
- In a p-type semiconductor, holes are majority carriers and electrons are minority carriers. Thermal excitation at room temperature produces both kinds of mobile carrier.

Step 1: Identify the dopant's role A boron atom has one fewer valence electron than the germanium atom it replaces. An incomplete covalent bond can accept an electron from a neighbouring bond, leaving a mobile hole. Thus acceptor doping increases the hole concentration and makes holes the majority charge carriers.

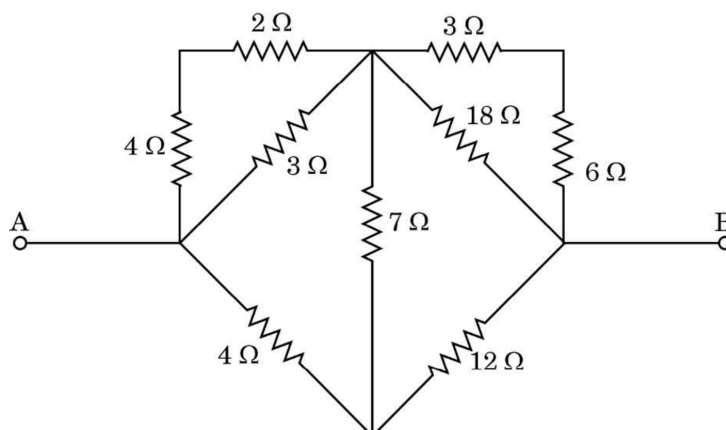
Step 2: Include the minority carriers At room temperature, some electrons are thermally excited into the conduction band, so their concentration is small but not zero. Therefore the material contains many holes and a few electrons. Option (B), holes only, incorrectly excludes thermal electrons. Option (A) excludes the majority holes, while option (D) describes an n-type majority-electron situation.

Step 3: Conclusion The charge carriers are holes and a few electrons. Hence, the correct option is (C).

Quick Tip to Solve: A trivalent impurity in tetravalent Ge gives p-type material; retain minority electrons whenever the temperature is above absolute zero.

7. The effective resistance between points A and B in the given circuit is:

[1 mark]



(A) 6Ω

(B) $\frac{8}{3} \Omega$

(C) $\frac{16}{3} \Omega$

(D) 2Ω

Correct Answer: (C) $\frac{16}{3} \Omega$

Solution:

Concept:

- Series resistances add; two parallel resistances give $R_p = R_1 R_2 / (R_1 + R_2)$.
- A Wheatstone bridge is balanced when the ratios of its corresponding arms are equal. Its central resistor then carries no current and does not affect the equivalent resistance.

Step 1: Reduce the upper arms Call the upper and lower diamond vertices C and D. Between A and C, the outer 4Ω and 2Ω resistors are in series, giving 6Ω , in parallel with 3Ω . Between C and B, the outer 3Ω and 6Ω give 9Ω , in parallel with 18Ω . Thus

$$R_{AC} = \frac{6 \times 3}{6 + 3} = 2 \Omega, \quad R_{CB} = \frac{9 \times 18}{9 + 18} = 6 \Omega.$$

Step 2: Test balance and combine the paths The lower arms are $R_{AD} = 4 \Omega$ and $R_{DB} = 12 \Omega$. Since

$$\frac{R_{AC}}{R_{CB}} = \frac{2}{6} = \frac{4}{12} = \frac{R_{AD}}{R_{DB}},$$

C and D are at equal potential. No current flows through the central 7Ω resistor. The paths ACB and ADB therefore have resistances 8Ω and 16Ω in parallel:

$$R_{AB} = \frac{8 \times 16}{8 + 16} = \frac{16}{3} \Omega.$$

Option (A) is only one reduced arm, and (D) is the other reduced upper arm; neither is the whole network. Option (B) is half the correctly calculated equivalent resistance.

Step 3: Conclusion The effective resistance is $\frac{16}{3} \Omega$. Hence, the correct option is (C).

Quick Tip to Solve: Reduce the two outer series paths first; the ratios 2 : 6 and 4 : 12 then reveal that the central 7Ω branch carries no current.

8. A capacitor and an inductor are connected in series across an ac source of voltage of variable frequency. The frequency is increased continuously. The nature of the circuit before and after the resonance will be: [1 mark]

- (A) inductive only
- (B) capacitive only
- (C) capacitive and inductive respectively
- (D) inductive and capacitive respectively

Correct Answer: (C) capacitive and inductive respectively

Solution:

Concept:

- Inductive reactance is $X_L = \omega L$, while capacitive reactance is $X_C = 1/(\omega C)$, where $\omega = 2\pi f$ is the angular frequency.
- The sign of $X_L - X_C$ determines the nature of a series circuit. At resonance, $\omega_0 = 1/\sqrt{LC}$ and the two reactances are equal.

Step 1: Compare reactances below resonance For $\omega < \omega_0$, $\omega^2 LC < 1$, so $\omega L < 1/(\omega C)$. Thus $X_C > X_L$ and the net reactance is negative. The circuit behaves capacitively, with current leading the applied voltage.

Step 2: Compare reactances above resonance As frequency rises, X_L increases and X_C decreases. Above ω_0 , $X_L > X_C$, giving positive net reactance and inductive behaviour. Options (A) and (B) wrongly assign one nature on both sides; option (D) reverses the actual order.

Step 3: Conclusion Before resonance the circuit is capacitive; after resonance it is inductive. Hence, the correct option is (C).

Quick Tip to Solve: At low frequency the capacitor dominates; at high frequency the inductor dominates. Use this order whenever frequency is increased through resonance.

9. An alternating current is given by $I = I_0 \cos(100\pi)t$. The least time the current takes to decrease from its maximum value to zero will be:

[1 mark]

- (A) $\left(\frac{1}{200}\right)$ s
(B) $\left(\frac{1}{150}\right)$ s
(C) $\left(\frac{1}{100}\right)$ s
(D) $\left(\frac{1}{50}\right)$ s

Correct Answer: (A) $\left(\frac{1}{200}\right)$ s

Solution:

Concept:

- For a sinusoidal current $I = I_0 \cos(\omega t)$, I_0 is its maximum value and ω is its angular frequency.
- A cosine decreases from its positive maximum to its first zero in one quarter of a cycle: $\Delta t = T/4 = \pi/(2\omega)$.

Step 1: Identify the phase change The printed expression is the usual alternating current with angular frequency $\omega = 100\pi \text{ rad s}^{-1}$. At $t = 0$, $I = I_0$. Its first subsequent zero occurs when the cosine argument reaches $\pi/2$, not π .

Step 2: Calculate the first zero time Setting $100\pi\Delta t = \pi/2$ gives

$$\Delta t = \frac{\pi}{2(100\pi)} = \frac{1}{200} \text{ s} = 0.005 \text{ s}.$$

Here $T = 2\pi/(100\pi) = 1/50 \text{ s}$. Thus option (D) is a full period, option (C) is half a period, and option (B) is one third of a period; none represents the first fall from the maximum to zero.

Step 3: Conclusion The least time is $\boxed{1/200 \text{ s}}$. Hence, the correct option is (A).

Quick Tip to Solve: For a cosine starting at its maximum, use one quarter of the period to reach zero; do not mistake angular frequency for ordinary frequency.

10. The mass numbers of two nuclei A and B are 27 and 64 respectively. The ratio of their radii $\left(\frac{r_A}{r_B}\right)$ will be: [1 mark]

- (A) $\frac{27}{64}$
(B) $\frac{9}{16}$
(C) $\frac{3\sqrt{3}}{8}$
(D) $\frac{3}{4}$

Correct Answer: (D) $\frac{3}{4}$

Solution:

Concept:

- A nuclear radius follows $r = r_0 A^{1/3}$, where A is the mass number and r_0 is an approximately common nuclear-radius constant.
- Hence the ratio of two nuclear radii is the cube root of their mass-number ratio; the common constant cancels.

Step 1: Form the radius ratio Denote the given mass numbers by $A_A = 27$ and $A_B = 64$. Applying the radius relation separately to both nuclei gives

$$\frac{r_A}{r_B} = \frac{r_0(27)^{1/3}}{r_0(64)^{1/3}} = \left(\frac{27}{64}\right)^{1/3}.$$

Step 2: Take the cube roots Since $27 = 3^3$ and $64 = 4^3$, the ratio is $3/4$. Option (A) uses the mass-number ratio directly; option (B) uses its two-thirds power, appropriate to an area ratio. Option (C), $3\sqrt{3}/8$, is its square root and also uses the wrong exponent for radius.

Step 3: Conclusion The ratio of the radii is $r_A/r_B = 3/4$. Hence, the correct option is (D).

Quick Tip to Solve: Recognise 27 and 64 as perfect cubes, then take their cube roots before forming the radius ratio.

11. Isotones are the nuclides having:

[1 mark]

- (A) same mass numbers
(B) same atomic numbers
(C) same neutron number, but different atomic number
(D) different neutron number, and different mass number

Correct Answer: (C) same neutron number, but different atomic number

Solution:

Concept:

- For a nuclide, the mass number is $A = Z + N$, where Z is the proton (atomic) number and N is the neutron number.
- Isotones are different nuclides with equal neutron numbers, whereas isotopes have equal atomic numbers and isobars have equal mass numbers.

Step 1: Apply the isotone condition Two isotones satisfy $N_1 = N_2$, or equivalently $A_1 - Z_1 = A_2 - Z_2$, while their atomic numbers differ. For example, ${}^{14}_6\text{C}$ and ${}^{15}_7\text{N}$ each contain eight neutrons but contain six and seven protons respectively.

Step 2: Distinguish the alternatives Option (A), equal mass numbers, describes isobars; option (B), equal atomic numbers, describes isotopes. Option (D) requires different neutron numbers and therefore contradicts the defining condition for isotones. Only option (C) keeps the neutron number equal while changing the atomic number.

Step 3: Conclusion Isotones have the same neutron number but different atomic numbers. Hence, the correct option is (C).

Quick Tip to Solve: For an isotone pair, calculate $A - Z$ for each nucleus: these neutron counts must match, while the proton counts differ.

12. A p-n junction diode is forward biased. As a result,

[1 mark]

- (A) both the potential barrier height and the width of depletion layer decrease.
- (B) both the potential barrier height and the width of depletion layer increase.
- (C) the potential barrier height decreases and the width of depletion layer increases.
- (D) the potential barrier height increases and the width of depletion layer decreases.

Correct Answer: (A) both the potential barrier height and the width of depletion layer decrease.

Solution:

Concept:

- In forward bias, the p-side is connected to the positive terminal and the n-side to the negative terminal of the supply.
- The applied electric field opposes the junction's built-in field, reducing the potential barrier that opposes majority-carrier diffusion.

Step 1: Determine the barrier change The forward voltage opposes the built-in junction potential. If the initial barrier potential is V_b and the applied forward voltage is V_F , the effective barrier is reduced approximately to $V_b - V_F$. Majority carriers can therefore cross the junction more easily.

Step 2: Determine the depletion-width change Forward bias drives holes from the p-side and electrons from the n-side towards the junction, reducing the region depleted of mobile charge carriers. The depletion layer consequently becomes narrower. Option (B) describes reverse-bias changes; options (C) and (D) each reverse one of the two forward-bias effects.

Step 3: Conclusion Both the potential barrier height and the depletion-layer width decrease. Hence, the correct option is (A).

Quick Tip to Solve: Recall the paired effect of forward bias: a lower barrier and a thinner depletion layer both make majority-carrier conduction easier.

13. Assertion (A): A ray of light is incident normally on the face of a prism. The emergent ray will graze along the opposite face of the prism when the critical angle at glass-air interface is equal to the angle of the prism.

Reason (R): The refractive index of a prism depends on angle of the prism.

Select the correct answer:

[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) Both Assertion (A) and Reason (R) are false.

Correct Answer: (C) Assertion (A) is true, but Reason (R) is false.

Solution:

Concept:

- For a prism of angle A_p , the internal angles of refraction obey $r_1 + r_2 = A_p$. Normal incidence gives $r_1 = 0$.
- At a glass-air interface, incidence at the critical angle C produces a refracted ray at 90° to the normal, grazing the surface; $\sin C = 1/\mu$ for air of index approximately one.

Step 1: Judge the assertion The ray enters the first face normally and is undeviated there. Thus $r_1 = 0$ and its incidence angle at the second face is $r_2 = A_p$. If $C = A_p$, the ray meets the second face at the critical angle, so its emergent ray grazes that face. The assertion is true.

Step 2: Judge the reason The refractive index is a property of the prism material for the given wavelength and physical conditions. It does not depend on the prism's geometrical angle. Changing the prism angle changes the path and deviation of a ray, not the material's refractive index. The reason is false.

Step 3: Check the explanatory link The grazing emergence follows from prism geometry and the critical-angle condition, not from the stated dependence of refractive index on prism angle. Options (A) and (B) wrongly treat the reason as true, while option (D) wrongly treats the assertion as false.

Step 4: Conclusion The assertion is true, but the reason is false. Hence, the correct option is (C).

Quick Tip to Solve: For normal entry into a prism, set $r_1 = 0$ immediately; the second-face incidence angle then equals the prism angle.

14. Assertion (A): A charged particle is moving with velocity v in x - y plane, making an angle θ ($0 < \theta < \frac{\pi}{2}$) with x -axis. If a uniform magnetic field $\vec{B}$ is applied in the region, along y -axis, the particle will move in a helical path with its axis parallel to x -axis.

Reason (R): The direction of the magnetic force acting on a charged particle moving in a magnetic field is along the velocity of the particle.

Select the correct answer:

[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) Both Assertion (A) and Reason (R) are false.

Correct Answer: (D) Both Assertion (A) and Reason (R) are false.

Solution:

Concept:

- Magnetic force is $\vec{F} = q \vec{v} \times \vec{B}$; it is perpendicular to both the velocity and magnetic field and does no work.
- A velocity component parallel to a uniform magnetic field remains constant, while a perpendicular component produces circular motion. Together they give a helix whose axis is parallel to the field.

Step 1: Judge the assertion With $\vec{B}$ along the y -axis, the parallel component is $v_y = v \sin \theta$, and the perpendicular component is $v_x = v \cos \theta$. Both are nonzero for the given angle range. The perpendicular component produces circular motion in the x - z plane while the particle progresses along y . The helix therefore has its axis parallel to the y -axis, not the x -axis. The assertion is false.

Step 2: Judge the reason From the cross product in $\vec{F} = q \vec{v} \times \vec{B}$, $\vec{F} \cdot \vec{v} = 0$. Thus the magnetic force is perpendicular to the instantaneous velocity, not along it. It changes the direction of motion without changing the speed. The reason is false.

Step 3: Check the explanatory link The proposed force direction cannot explain the motion because it contradicts the magnetic-force law. The correct helical motion follows from the simultaneous perpendicular circular motion and unchanged parallel motion. Options (A), (B) and (C) all incorrectly declare the assertion true.

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

Quick Tip to Solve: To locate a magnetic helix's axis, look at the direction of the magnetic field; the unchanged velocity component runs along that axis.

15. Assertion (A): The minimum negative potential applied to the anode in a photoelectric experiment at which photoelectric current becomes zero, is called cut-off voltage.

Reason (R): The threshold frequency for a metal is the minimum frequency of incident radiation below which emission of photoelectrons does not take place.

Select the correct answer:

[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) Both Assertion (A) and Reason (R) are 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:

- The stopping or cut-off potential has magnitude V_0 , where $eV_0 = K_{\max}$; e is the magnitude of electron charge.
- The threshold frequency ν_0 is fixed by the work function $\phi = h\nu_0$, where h is Planck's constant.

Step 1: Judge Assertion (A) A negative anode potential opposes the motion of emitted electrons. At the stopping potential even the fastest photoelectrons cannot reach the anode, so the photocurrent becomes zero. This is precisely the definition given in A, and A is true.

Step 2: Judge Reason (R) Photoemission requires the photon energy $h\nu$ to be at least the work function. For $\nu < \nu_0$, this condition fails and emission does not occur. R correctly defines threshold frequency and is true.

Step 3: Test the explanatory connection R concerns the minimum photon energy needed to release electrons, whereas A concerns stopping electrons after they have been released. The definition of threshold frequency does not explain the retarding action of the anode potential. Thus option (A) is ruled out; (C) and (D) incorrectly declare a true statement false.

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

Quick Tip to Solve: Distinguish the threshold for emission from the voltage required to stop already emitted electrons.

16. Assertion (A): EM waves do not require a medium for their propagation.

Reason (R): EM waves are transverse waves.

Select the correct answer:

[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) Both Assertion (A) and Reason (R) are 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:

- An electromagnetic wave consists of oscillating electric and magnetic fields that can propagate in vacuum, with speed $c = 1/\sqrt{\mu_0\epsilon_0}$.
- In a plane electromagnetic wave, $\vec{E}$ and $\vec{B}$ are perpendicular to each other and to the direction of propagation; this is transverse character.

Step 1: Judge Assertion (A) Electromagnetic waves transfer energy through changing electric and magnetic fields. They do not require material particles to oscillate, and they propagate through vacuum. Therefore A is true.

Step 2: Judge Reason (R) The field oscillations are perpendicular to the propagation direction, so electromagnetic waves are transverse. Therefore R is also true.

Step 3: Check whether R explains A Transverse character specifies the orientation of oscillation, not whether a medium is needed. For example, transverse waves on a stretched string do require a material medium. Thus R does not explain A. Option (A) mistakes a property for an explanation; options (C) and (D) contradict the truth of the statements.

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

Quick Tip to Solve: For an assertion about a medium, ask what actually oscillates; transverse orientation alone does not decide it.

Section B (10 marks)

17. Two wires made of the same material have the same length (l) but different cross-sectional areas A_1 and A_2 . They are connected together with a cell of voltage V . Find the ratio of the drift velocities of free electrons in the two wires when they are joined in (i) series, and (ii) parallel.

[2 marks]

Solution:

Concept:

- The magnitude of drift velocity is $v_d = I/(neA)$, where I is current, n is free-electron number density, e is electron charge magnitude and A is cross-sectional area.
- A uniform wire has resistance $R = \rho l/A$. For the same material at the same temperature, resistivity

ρ and carrier density n are the same.

Step 1: Compare drift velocities in series The same current I passes through both wires in series. Hence the number of charge carriers crossing each section per second is the same, although the cross-sectional areas differ:

$$\frac{v_{d1}}{v_{d2}} = \frac{I/(neA_1)}{I/(neA_2)} = \frac{A_2}{A_1}.$$

Thus the thinner wire has the greater drift-speed magnitude. The common current depends on the total resistance, but cancels in this ratio.

Step 2: Compare drift velocities in parallel Each wire now has the same potential difference V across the same length l . Using Ohm's law separately for each branch gives

$$I_1 = \frac{VA_1}{\rho l}, \quad I_2 = \frac{VA_2}{\rho l}.$$

Substitution into the drift formula yields

$$v_{d1} = \frac{V}{ne\rho l}, \quad v_{d2} = \frac{V}{ne\rho l}.$$

The larger current in the thicker wire is exactly compensated by its larger area. Equivalently, both wires have the same electric field $E = V/l$.

Step 3: Conclusion The ratios of drift-speed magnitudes are (i) series: $v_{d1} : v_{d2} = A_2 : A_1$, and (ii) parallel: $v_{d1} : v_{d2} = 1 : 1$.

Quick Tip to Solve: In series cancel the common current in $v_d = I/(neA)$; in parallel compare the fields V/l .

18. Draw energy band diagrams of n-type and p-type semiconductors at temperature $T > 0$ K. Show the donor/acceptor energy levels with the order of difference of their energies from the bands.

[2 marks]

Solution:

Concept:

- Doping introduces discrete energy levels inside the forbidden gap of a semiconductor. Let E_C denote the bottom of the conduction band and E_V the top of the valence band.
- A donor level E_D lies just below E_C , while an acceptor level E_A lies just above E_V . Their separation from the nearby band edge is of order 10^{-2} eV, much smaller than the band gap.

Step 1: Draw the n-type energy levels A pentavalent impurity supplies a weakly bound extra electron. Draw its donor level close to and below the conduction-band edge. At a suitable temperature above absolute zero, thermal energy can excite donor electrons into the conduction band, leaving ionised donors behind:

$$E_C - E_D \sim 10^{-2} \text{ eV}.$$

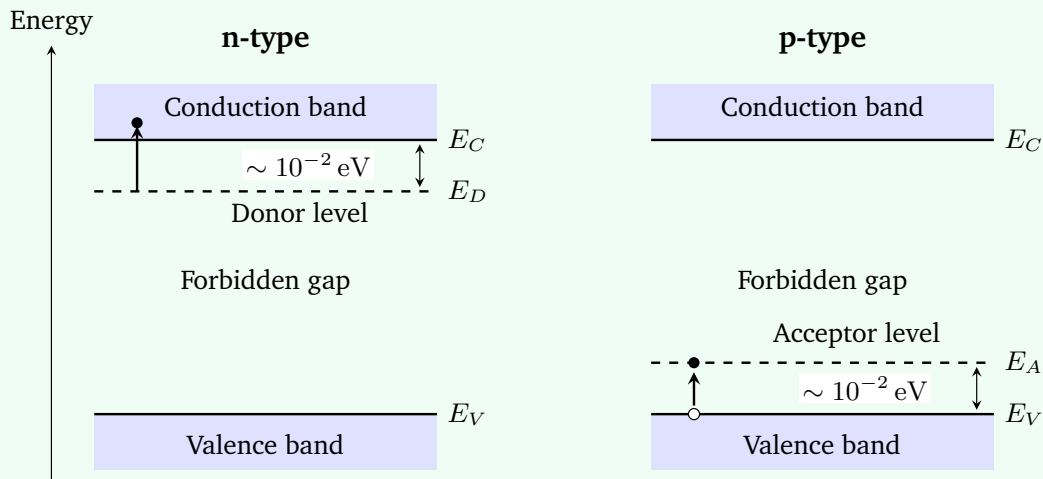
Electrons are the majority carriers. The arrow shows excitation from the donor level.

Step 2: Draw the p-type energy levels A trivalent impurity creates an acceptor level just above the valence-band edge. A valence electron can gain a small amount of thermal energy and occupy this

level, leaving a mobile hole in the valence band:

$$E_A - E_V \sim 10^{-2} \text{ eV}.$$

Holes are the majority carriers. The arrow shows excitation to the acceptor level; the open circle is the hole left behind.



Energy bands at $T > 0 \text{ K}$: filled circles denote electrons and the open circle a hole. Energy increases upwards; spacings are schematic.

Step 3: Conclusion For n-type material, the donor level is just below the conduction band; for p-type material, the acceptor level is just above the valence band. Each impurity level is typically of order 0.01 eV from its adjacent band edge.

Quick Tip to Solve: Put the donor level near the band receiving donated electrons, and the acceptor level near the band losing an electron.

19. The ratio of the intensities at maxima to minima in Young's double-slit experiment is 25 : 9. Calculate the ratio of intensities of the interfering waves. [2 marks]

Solution:

Concept:

- For two coherent waves of amplitudes a_1 and a_2 , the resultant amplitudes at constructive and destructive interference are $a_1 + a_2$ and $|a_1 - a_2|$.
- Intensity is proportional to the square of amplitude. Thus $I_{\max}/I_{\min} = (a_1 + a_2)^2/(a_1 - a_2)^2$, while the individual intensity ratio is $I_1/I_2 = a_1^2/a_2^2$.

Step 1: Find the amplitude ratio from the fringe contrast Label the stronger wave as wave 1, so $a_1 > a_2$. Taking the positive square root of the given maximum-to-minimum intensity ratio gives

$$\frac{a_1 + a_2}{a_1 - a_2} = \sqrt{\frac{25}{9}} = \frac{5}{3}.$$

Let $r = a_1/a_2$. Cross-multiplication gives

$$\begin{aligned}3(r + 1) &= 5(r - 1), \\3r + 3 &= 5r - 5, \\2r &= 8, \quad r = 4.\end{aligned}$$

The amplitudes therefore have ratio 4 : 1; this intermediate ratio is not yet the ratio of the individual intensities.

Step 2: Convert amplitudes into individual intensities Squaring the amplitude ratio gives

$$\frac{I_1}{I_2} = \left(\frac{a_1}{a_2}\right)^2 = 4^2 = 16.$$

To check, amplitudes $4a$ and a produce maximum and minimum intensities proportional to $(5a)^2$ and $(3a)^2$, reproducing the given 25 : 9. Equal wave intensities would instead make the minimum zero, so that case cannot apply here.

Step 3: Conclusion The intensities of the interfering waves are in the ratio 16 : 1, taking the stronger wave first (or 1 : 16 if their labels are reversed).

Quick Tip to Solve: Take square roots of the fringe intensities first, form the sum-to-difference ratio, then square the resulting amplitude ratio.

20(a). Using the mirror equation and the formula of magnification, deduce that “the virtual image produced by a convex mirror is always diminished in size and is located between the pole and the focus.” [2 marks]

Solution:

Concept:

- The mirror equation is $1/f = 1/v + 1/u$, where u , v and f are signed object distance, image distance and focal length.
- With the Cartesian sign convention, a real object in front of a convex mirror has $u < 0$, while $f > 0$. Transverse magnification is $m = h_i/h_o = -v/u$.

Step 1: Apply the mirror equation with signed distances Let the real object be a finite distance $a > 0$ in front of the mirror, so that $u = -a$. Then

$$\frac{1}{v} = \frac{1}{f} - \frac{1}{u} = \frac{1}{f} + \frac{1}{a}, \quad v = \frac{af}{a + f}.$$

Since both a and f are positive, $v > 0$: the image is behind the mirror and is virtual. Also $v/f = a/(a + f) < 1$, so $0 < v < f$. This places the image strictly between the pole and focus for every finite real-object distance.

Step 2: Evaluate the magnification Substituting the same signed distances into the magnification formula gives

$$m = -\frac{v}{u} = \frac{v}{a} = \frac{f}{a + f}.$$

Thus $0 < m < 1$. The positive sign means that the image is erect, while the magnitude below unity means that its height is smaller than the object's height. As the object recedes to infinity, the image

approaches the focus as a limiting position.

Step 3: Conclusion A convex mirror forms an erect, virtual, diminished image of a real object: $0 < m < 1$ and $0 < v < f$, so the image lies between its pole and focus (at the focus in the infinite-distance limit).

Quick Tip to Solve: Put $u = -a$ with $a > 0$ before using the mirror equation; the positive denominators immediately reveal both image position and size.

OR

20(b). A convex lens of focal length 10 cm, a concave lens of focal length 15 cm and a third lens of unknown focal length are placed coaxially in contact. If the focal length of the combination is +12 cm, find the nature and focal length of the third lens, if all lenses are thin. Will the answer change if the lenses were thick? [2 marks]

Solution:

Concept:

- For thin lenses coaxially in contact in air, their powers add: $1/F = 1/f_1 + 1/f_2 + 1/f_3$, where F is the equivalent focal length.
- A converging convex lens has positive focal length, whereas a diverging concave lens has negative focal length. All lengths in a reciprocal-length equation must use the same unit.

Step 1: Substitute the signed focal lengths Here $f_1 = +10$ cm, $f_2 = -15$ cm and $F = +12$ cm. The given magnitude for the concave lens must carry a negative sign. Hence

$$\begin{aligned}\frac{1}{f_3} &= \frac{1}{12} - \frac{1}{10} - \frac{1}{-15} \\ &= \frac{5 - 6 + 4}{60} = \frac{1}{20} \text{ cm}^{-1}.\end{aligned}$$

The unknown lens therefore supplies positive power. As a check, the known lenses together have power $10 - 6.67 = 3.33$ D; adding 5.00 D gives the required 8.33 D.

Step 2: Examine the thick-lens case Yes, the thin-lens result can change for thick lenses. The simple addition used above assumes negligible thickness and coincident lens planes. For thick lenses, the principal planes need not coincide even when their surfaces touch, so thickness and effective separation affect the equivalent power. Additional information about the lenses is needed to calculate a revised value; +20 cm is not guaranteed in that case.

Step 3: Conclusion The third thin lens has $f_3 = +20$ cm and is converging (convex). For thick lenses, the result generally changes and cannot be determined uniquely from the supplied data alone.

Quick Tip to Solve: Assign a negative focal length to the concave lens before subtracting the known powers from the total; subtracting its power then adds a positive term.

21. Calculate the binding energy per nucleon (in MeV) of a helium nucleus (${}^4_2\text{He}$).

Given: $m({}^4_2\text{He}) = 4.002603 \text{ u}$, $m_n = 1.008665 \text{ u}$, $m_H = 1.007825 \text{ u}$, $1 \text{ u} = 931.5 \text{ MeV}/c^2$.

[2 marks]

Solution:

Concept:

- Binding energy is the mass defect expressed as energy: $B = \Delta mc^2$. The binding energy per nucleon is B/A , where A is the mass number.
- Using atomic masses, $\Delta m = Zm_H + (A - Z)m_n - M_{\text{atom}}$. Here m_H is the hydrogen-atom mass and m_n the neutron mass; the electron masses cancel between the neutral atoms.

Step 1: Calculate the mass defect Helium-4 contains $Z = 2$ protons and $A - Z = 2$ neutrons. The printed value 1.007825 u is the hydrogen-atom mass, and 4.002603 u is the helium atomic mass. Using these consistently includes two electrons on either side, so their rest masses cancel (atomic electron binding energies are negligible here).

$$\begin{aligned}\Delta m &= 2m_H + 2m_n - m({}^4_2\text{He}) \\ &= 2(1.007825) + 2(1.008665) - 4.002603 \\ &= 0.030377 \text{ u}.\end{aligned}$$

The positive defect means that the bound system has less mass than its separated constituents.

Step 2: Convert to energy and divide by the nucleon count Since $1 \text{ u} c^2 = 931.5 \text{ MeV}$, the total energy needed to separate the nucleus is

$$B = 0.030377 \times 931.5 = 28.2962 \text{ MeV}.$$

There are four nucleons, not just the two protons, so

$$\frac{B}{A} = \frac{28.2962}{4} = 7.07404 \text{ MeV per nucleon}.$$

Step 3: Conclusion The binding energy per nucleon of the helium-4 nucleus is approximately 7.07 MeV per nucleon.

Quick Tip to Solve: When the supplied mass is m_H , use atomic masses so electron masses cancel; divide the total binding energy by $A = 4$, not by $Z = 2$.

Section C (21 marks)

22. Write the mathematical forms of three postulates of Bohr's theory of the hydrogen atom. Using them prove that, for an electron revolving in the n^{th} orbit,

(a) the radius of the orbit is proportional to n^2 , and

(b) the total energy of the atom is proportional to $\left(\frac{1}{n^2}\right)$.

[3 marks]

Solution:

Concept:

- Bohr's model has non-radiating stationary orbits, quantised angular momentum, and emission or absorption only in transitions between allowed energies.

- For hydrogen, Coulomb attraction supplies centripetal force: $m_e v_n^2 / r_n = k e^2 / r_n^2$, with $k = 1/(4\pi\epsilon_0)$, electron mass m_e , and elementary charge magnitude e .
- The zero of potential energy is at infinite separation. Thus $U_n = -k e^2 / r_n$, kinetic energy is $K_n = m_e v_n^2 / 2$, and $E_n = K_n + U_n$.

Step 1: State the three postulates mathematically First, the electron moves in a permitted stationary orbit without radiating: its energy stays fixed, $E = E_n$, with $dE_n/dt = 0$ while it remains in that orbit. Its circular motion obeys

$$\frac{m_e v_n^2}{r_n} = \frac{k e^2}{r_n^2}.$$

Second, only those orbits with quantised angular momentum are allowed:

$$m_e v_n r_n = \frac{n h}{2\pi} = n \hbar, \quad n = 1, 2, 3, \dots$$

Third, a photon is emitted or absorbed only during a transition, with

$$h\nu = |E_i - E_f|.$$

Emission has $E_i > E_f$, and absorption has $E_f > E_i$. Here h is Planck's constant and $\hbar = h/(2\pi)$.

Step 2: Derive the radius dependence for part (a) From angular-momentum quantisation, $v_n = n\hbar/(m_e r_n)$. Substitute this into the circular-orbit force equation:

$$m_e \left(\frac{n\hbar}{m_e r_n} \right)^2 = \frac{k e^2}{r_n},$$

$$r_n = \frac{n^2 \hbar^2}{m_e k e^2} = \frac{\epsilon_0 \hbar^2}{\pi m_e e^2} n^2.$$

All factors except n^2 are constants for hydrogen, establishing the required radius dependence.

Step 3: Derive the total energy dependence for part (b) The force equation gives $m_e v_n^2 = k e^2 / r_n$, so the positive kinetic energy is half the magnitude of the negative potential energy:

$$E_n = \frac{k e^2}{2 r_n} - \frac{k e^2}{r_n} = -\frac{k e^2}{2 r_n},$$

$$E_n = -\frac{m_e k^2 e^4}{2 \hbar^2} \frac{1}{n^2} = -\frac{m_e e^4}{8 \epsilon_0^2 \hbar^2} \frac{1}{n^2}.$$

The proportionality coefficient is negative because the electron is bound. Thus the printed inverse-square dependence refers to $E_n = -C/n^2$, with a positive constant C , and does not imply positive total energy.

Step 4: Conclusion The allowed radii satisfy $r_n \propto n^2$. The total energies satisfy $E_n = -C/n^2$, where $C = m_e e^4 / (8 \epsilon_0^2 \hbar^2) > 0$; hence the energy has the required inverse-square dependence with a negative coefficient.

Quick Tip to Solve: Combine the force equation with $m_e v r = n\hbar$ to find r_n ; then use $E_n = -k e^2 / (2 r_n)$ instead of calculating the speed again.

23. (a) Briefly explain Einstein's photoelectric equation.

(b) Four metals with their work functions are listed below:

$K = 2.3 \text{ eV}$, $Na = 2.75 \text{ eV}$, $Mo = 4.17 \text{ eV}$ and $Ni = 5.15 \text{ eV}$.

The radiation of wavelength 330 nm from a laser source placed 1 m away, falls on these metals. Which of these metals will not show photoelectric emission? What will happen if the laser source is brought closer to a distance of 50 cm? [3 marks]

Solution:

Concept:

- A photon of frequency ν has energy $h\nu = hc/\lambda$; one photon transfers its energy to one electron in the usual photoelectric process.
- The work function ϕ is the minimum energy needed to escape the metal. Einstein's equation is $h\nu = \phi + K_{\max}$, where $K_{\max}$ is the maximum emitted-electron kinetic energy.

Step 1: (a) Apply conservation of energy Part of the absorbed photon's energy overcomes the binding of the electron and the remainder becomes kinetic energy:

$$h\nu = \phi + \frac{1}{2}mv_{\max}^2, \quad K_{\max} = h\nu - \phi.$$

Here h is Planck's constant, m is the electron mass and $v_{\max}$ is its maximum speed. Electrons suffering energy loss inside the metal emerge with smaller energies. Emission requires $h\nu \geq \phi$, giving threshold frequency $\nu_0 = \phi/h$.

Step 2: (b) Compare the photon energy with each work function Using $hc \simeq 1240 \text{ eV nm}$, the incident photon energy is

$$E = \frac{1240}{330} \text{ eV} \simeq 3.76 \text{ eV}.$$

For potassium and sodium, $3.76 > 2.3$ and $3.76 > 2.75$, so emission is possible. Their maximum kinetic energies are approximately 1.46 eV and 1.01 eV, respectively. For molybdenum and nickel, $3.76 < 4.17$ and $3.76 < 5.15$; the individual photons cannot overcome their work functions.

Step 3: Determine the effect of moving the source closer Changing the distance from 1 m to 50 cm does not change the laser wavelength, hence it does not change photon energy or $K_{\max}$. If the incident intensity increases on moving the source closer, more electrons per second are emitted from K and Na, increasing the photoelectric current under the same collection conditions. The increase in intensity still cannot initiate ordinary photoelectric emission from Mo or Ni. The precise intensity change depends on the laser beam's spreading and need not follow an inverse-square law for a collimated beam.

Step 4: Conclusion Einstein's equation is $h\nu = \phi + K_{\max}$. Mo and Ni do not emit at 330 nm, even at 50 cm. Greater incident intensity increases the emission rate from K and Na, while their maximum kinetic energies remain unchanged.

Quick Tip to Solve: Convert wavelength to photon energy using 1240 divided by wavelength in nm; compare that energy with each work function before considering intensity.

24(a). (i) Write Biot-Savart's law in vector form.

(ii) Two identical circular coils A and B , each of radius R , carrying currents I and $\sqrt{3}I$ respectively, are placed concentrically in XY and YZ planes respectively. Find the magnitude and direction of the net magnetic field at their common centre.

[3 marks]

Solution:

Concept:

- Biot-Savart's law gives the field of a current element: $d\vec{B} = (\mu_0/4\pi)I d\vec{l} \times \hat{r}/r^2$, where $\hat{r}$ points from the element to the observation point.
- At the centre of a circular loop of radius R , $B = \mu_0 I/(2R)$. The field is normal to the loop according to the right-hand rule.
- Magnetic fields add as vectors. Fields normal to mutually perpendicular coil planes are perpendicular, so their resultant magnitude follows Pythagoras' theorem.

Step 1: (i) **State the vector law and define its symbols** For a current element carrying steady current I ,

$$d\vec{B} = \frac{\mu_0}{4\pi} \frac{I d\vec{l} \times \hat{r}}{r^2} = \frac{\mu_0}{4\pi} \frac{I d\vec{l} \times \vec{r}}{r^3}.$$

Here $d\vec{l}$ points along conventional current, $\vec{r}$ runs from the current element to the field point, and μ_0 is the permeability of free space. The cross product fixes the field's direction.

Step 2: (ii) **Find the perpendicular component fields** Coil A lies in the XY plane, so its field is along the Z -axis; coil B lies in the YZ plane, so its field is along the X -axis. Their magnitudes are

$$B_A = \frac{\mu_0 I}{2R}, \quad B_B = \frac{\sqrt{3}\mu_0 I}{2R} = \sqrt{3}B_A.$$

Thus $\vec{B}_A \perp \vec{B}_B$. For fields directed along positive Z and positive X , respectively,

$$\vec{B}_{\text{net}} = \frac{\mu_0 I}{2R}(\sqrt{3}\hat{i} + \hat{k}).$$

Step 3: **Calculate the resultant magnitude and direction** Vector addition gives

$$B_{\text{net}} = \sqrt{B_A^2 + B_B^2} = \frac{\mu_0 I}{2R}\sqrt{1+3} = \frac{\mu_0 I}{R}.$$

If θ is the angle measured from $\vec{B}_A$ towards $\vec{B}_B$, then $\tan \theta = B_B/B_A = \sqrt{3}$, so $\theta = 60^\circ$. Equivalently, the resultant makes 30° with $\vec{B}_B$, in the XZ plane. The printed question does not specify either current's circulation sense, so the signs along X and Z must be assigned using the right-hand rule; the magnitude and the angles relative to the actual component fields are unchanged. The loop formula assumes single turns; if both coils have N turns, every field is multiplied by N .

Step 4: Conclusion For single-turn coils, $B_{\text{net}} = \mu_0 I/R$, directed in the XZ plane at 60° to coil A 's field and 30° to coil B 's field. The direction senses depend on the two current circulations.

Quick Tip to Solve: First draw each coil's normal mentally: XY gives Z and YZ gives X . Add the perpendicular field magnitudes in quadrature, never directly.

24(b). (i) A rectangular loop of sides l and b carries a current I clockwise. Write the magnetic moment $\vec{m}$ of the loop and show its direction in a diagram.

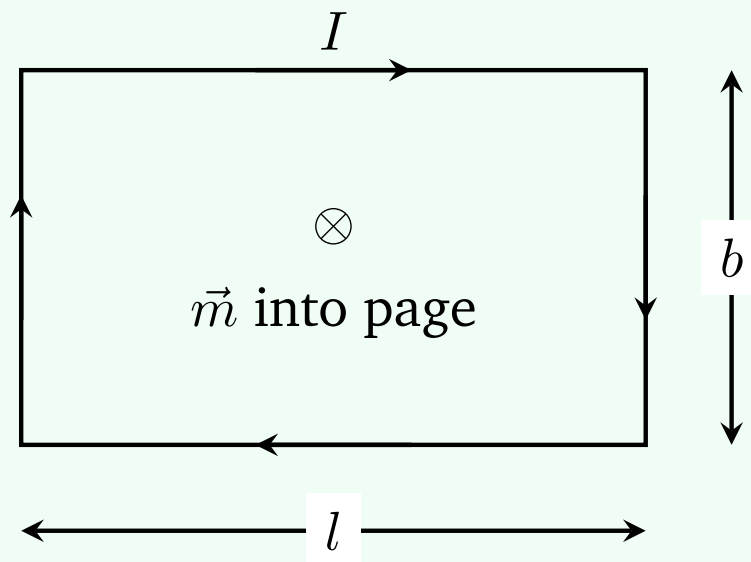
(ii) The loop is placed in a uniform magnetic field $\vec{B}$ and is free to rotate about an axis which is perpendicular to $\vec{B}$. Prove that the loop experiences no net force, but a torque $\vec{\tau} = \vec{m} \times \vec{B}$. [3 marks]

Solution:

Concept:

- The magnetic moment of a plane current loop is $\vec{m} = IA\hat{n}$, where A is its area and $\hat{n}$ is the right-hand-rule normal.
- A straight conductor segment in a uniform magnetic field experiences $\vec{F} = I\vec{L} \times \vec{B}$. Equal opposite forces can form a couple even when their resultant force is zero.

Step 1: (i) Determine the magnetic moment The loop area is $A = lb$, so $\vec{m} = Ilb\hat{n}$. Curling the fingers of the right hand along the clockwise current makes the thumb point into the page. Thus the magnetic moment is normal to the loop, into the page as viewed in the drawing. With $+\hat{k}$ out of the page, $\vec{m} = -Ilb\hat{k}$, of magnitude Ilb and SI unit $A\ m^2$.



Clockwise current gives magnetic moment into the page; the cross denotes the inward normal.

Step 2: (ii) Show that the net force vanishes Opposite sides carry currents in opposite directions and have equal lengths. Since $\vec{B}$ is uniform, their magnetic forces are equal and opposite. Equivalently,

$$\vec{F}_{\text{net}} = I \oint d\vec{l} \times \vec{B} = I \left(\oint d\vec{l} \right) \times \vec{B} = \vec{0}.$$

The integral of the displacement around any closed loop is zero. This cancellation requires the same field at all segments.

Step 3: Derive the magnitude and direction of the torque Let θ be the angle between the loop normal $\hat{n}$ and $\vec{B}$. Resolve the field into a normal component $B \cos \theta$ and an in-plane component $B \sin \theta$. The normal component produces no net turning moment. To evaluate the couple, first take the in-plane component parallel to the sides of length b . The two sides of length l then experience opposite forces

of magnitude $F = IlB \sin \theta$, normal to the loop. Their lines of action are separated by b , hence

$$\tau = Fb = IlbB \sin \theta = mB \sin \theta.$$

The force directions from $I\vec{L} \times \vec{B}$ make the loop turn so that $\vec{m}$ tends to align with $\vec{B}$. The torque direction is therefore $\hat{n} \times \vec{B}$. For an arbitrary in-plane field direction, resolve it along the two side directions; the corresponding couples add vectorially to the same result. Thus $\vec{\tau} = Ilb\hat{n} \times \vec{B}$. Its axis is perpendicular to $\vec{B}$, consistent with the stated freedom to rotate.

Step 4: Conclusion $\vec{m} = Ilb\hat{n}$, into the page for clockwise current; $\vec{F}_{\text{net}} = \vec{0}$, while $\vec{\tau} = \vec{m} \times \vec{B}$ and $\tau = IlbB \sin \theta$.

Quick Tip to Solve: Curl your right-hand fingers along the loop current for the moment direction; in the torque formula use the angle between the normal and the field.

25. (a) How are electromagnetic waves produced?

(b) Write the wavelength range and one use of:

(i) Microwaves, and

(ii) Ultraviolet waves.

[3 marks]

Solution:

Concept:

- An accelerating electric charge radiates electromagnetic waves; an oscillating charge is a common source.
- In vacuum, wavelength λ and frequency ν obey $c = \nu\lambda$, where c is the speed of light. Spectral bands have conventional approximate boundaries.

Step 1: Explain the production of electromagnetic waves (a) When an electric charge accelerates, its electric field changes with time. The changing electric field is associated with a time-varying magnetic field, and the coupled fields propagate away from the source as an electromagnetic wave. For example, charges oscillating in an antenna emit such waves at the oscillation frequency. A stationary charge produces only a static electric field and does not radiate.

Step 2: State the microwave range and its application (b)(i) The approximate wavelength range of microwaves is

$$1 \text{ mm to } 0.1 \text{ m} \quad (10^{-3} \text{ m to } 10^{-1} \text{ m}).$$

One use is in radar systems for locating aircraft. A directed microwave pulse reflects from the aircraft, and the delay of the returning pulse gives its distance. Their short wavelengths allow suitably directed beams.

Step 3: State the ultraviolet range and its application (b)(ii) Ultraviolet waves have approximate wavelengths

$$1 \text{ nm to } 400 \text{ nm} \quad (10^{-9} \text{ m to } 4 \times 10^{-7} \text{ m}).$$

One use is sterilisation of water or surgical instruments. Suitable ultraviolet radiation destroys microorganisms, enabling disinfection. Ultraviolet wavelengths are shorter than those of visible violet light.

Step 4: Conclusion Accelerating charges produce electromagnetic waves. Microwaves, approximately 1 mm to 0.1 m, are used in radar; ultraviolet waves, approximately 1 nm to 400 nm, are used for

sterilisation.

Quick Tip to Solve: Pair each band with a familiar use: microwaves with radar and ultraviolet with sterilisation; convert nanometres using $1 \text{ nm} = 10^{-9} \text{ m}$.

26. (a) Two concentric circular coils of radii r_1 and r_2 ($r_2 \gg r_1$) are placed coaxially with their centres coinciding. If a current I is passed through the outer coil, obtain the expression for mutual inductance of the arrangement.

(b) The current in a solenoid decreases steadily from 6 mA to 2 mA in 50 ms. If an average emf of 0.4 V is induced, find the self-inductance of the solenoid. [3 marks]

Solution:

Concept:

- Mutual inductance M relates flux linkage in one coil to current in the other: $\Phi_1 = MI$ for a single-turn receiving coil.
- A circular loop of radius R carrying current I produces the central field $B = \mu_0 I / (2R)$, where μ_0 is the permeability of free space.
- Self-induced emf obeys $\varepsilon = -L dI/dt$; L is the self-inductance and the minus sign expresses Lenz's law.

Step 1: Find the magnetic field over the smaller coil (a) The much larger outer coil has radius r_2 , so its field is approximately uniform over the inner coil of radius r_1 . The printed inequality uses r ; here it denotes the smaller radius r_1 . Since the coils are coaxial, the field is perpendicular to the inner coil's plane. For single-turn coils, the central field is $B_2 = \mu_0 I / (2r_2)$.

Step 2: Calculate flux and divide by the source current The inner coil has area $A_1 = \pi r_1^2$. Its magnetic flux is therefore

$$\Phi_1 \simeq B_2 A_1 = \frac{\mu_0 I \pi r_1^2}{2r_2}.$$

Using the definition $M = \Phi_1 / I$, the mutual-inductance magnitude is

$$M \simeq \frac{\mu_0 \pi r_1^2}{2r_2}.$$

The approximation neglects field variation across the small coil.

Step 3: Convert the current change and calculate self-inductance (b) The current changes uniformly, so

$$\Delta I = (2 - 6) \times 10^{-3} = -4 \times 10^{-3} \text{ A},$$

$$\Delta t = 50 \times 10^{-3} \text{ s},$$

$$\frac{\Delta I}{\Delta t} = -0.08 \text{ A s}^{-1}.$$

Taking the magnitude of the induced emf,

$$L = \frac{|\varepsilon|}{|\Delta I / \Delta t|} = \frac{0.4}{0.08} = 5 \text{ H}.$$

The induced emf acts to maintain the original current, opposing its decrease; inductance itself is positive.

Step 4: Conclusion (a) $M \simeq \mu_0 \pi r_1^2 / (2r_2)$ for single-turn coils with $r_2 \gg r_1$. (b) The solenoid's

self-inductance is $L = 5 \text{ H}$.

Quick Tip to Solve: Use the outer radius to find the field and the inner radius to find the flux area. In the numerical part, both milli-factors cancel in $\Delta I/\Delta t$.

27. Explain the process of formation of ‘depletion layer’ and ‘potential barrier’ in a p-n junction region of a diode, with the help of a suitable diagram. Which feature of junction diode makes it suitable for its use as a rectifier? [3 marks]

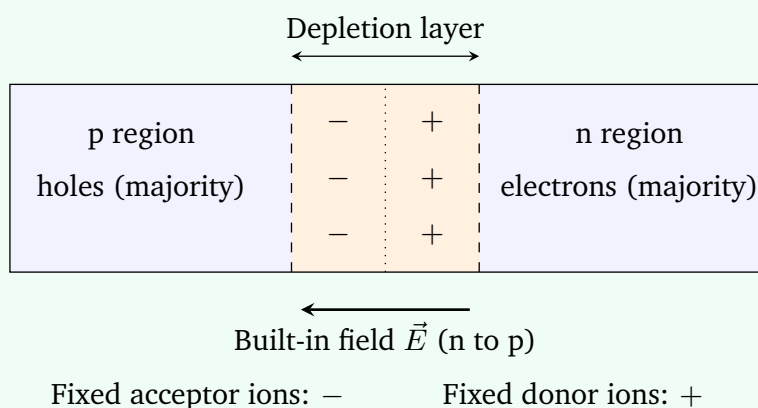
Solution:

Concept:

- Majority carriers diffuse down their concentration gradients and recombine near a p-n junction.
- Fixed ionised dopants create a space-charge region and an electric field. The associated potential barrier opposes further majority-carrier diffusion.
- A diode has low resistance in forward bias and very high resistance in reverse bias, below breakdown, giving predominantly one-way conduction.

Step 1: Explain diffusion and depletion-layer formation Immediately after the p and n regions form a junction, electrons diffuse from the n side into the p side, while holes diffuse from the p side into the n side. They recombine near the junction. Electrons leaving the n side expose immobile positive donor ions, and holes leaving the p side expose immobile negative acceptor ions. Thus a thin region near the junction becomes depleted of mobile charge carriers. This region is the depletion layer; it contains fixed ions and is not devoid of all charge.

Step 2: Explain the potential barrier The positive ions on the n side and negative ions on the p side establish an electric field directed from n to p. This field opposes the diffusion of majority carriers: it drives electrons towards n and holes towards p. Its associated potential difference is the built-in potential barrier. As the layer develops, the opposing drift current increases until it balances diffusion current. At thermal equilibrium, the net current is zero.



Unbiased p-n junction: immobile ions and the built-in electric field in the depletion layer.

Step 3: Identify the property responsible for rectification Forward bias lowers the barrier and permits appreciable current, whereas reverse bias raises the barrier and permits only a very small reverse current before breakdown. Consequently, a diode conducts readily during one polarity of an alternating voltage and blocks the other. This asymmetric current-voltage behaviour allows it to convert alternating current into unidirectional, pulsating current in a rectifier.

Step 4: Conclusion Fixed ions form the depletion layer and its potential barrier. The diode rectifies

because it conducts readily in forward bias and blocks in reverse bias.

Quick Tip to Solve: Draw negative fixed ions on the p side and positive fixed ions on the n side; the built-in electric-field arrow must point from n to p.

28. Two point charges of $-5 \mu\text{C}$ and $2 \mu\text{C}$ are located in free space at $(-4 \text{ cm}, 0)$ and $(6 \text{ cm}, 0)$ respectively.

(a) Calculate the amount of work done to separate the two charges at infinite distance.

(b) If this system of charges was initially kept in an electric field $E = \frac{A}{r^2}$, where $A = 8 \times 10^4 \text{ N C}^{-1} \text{ m}^2$, calculate the electrostatic potential energy of the system. [3 marks]

Solution:

Concept:

- The mutual potential energy of two point charges is $U_{12} = kq_1q_2/r_{12}$, with $k = 9 \times 10^9 \text{ N m}^2\text{C}^{-2}$ and zero energy at infinite separation.
- Quasistatic external work is the increase in potential energy: $W_{\text{ext}} = U_f - U_i$. For an outward radial inverse-square field, $E_r = -dV/dr$ gives $V(r) = A/r$, taking $V(\infty) = 0$.
- In an external field, the energy of the two-charge system is $U = q_1V(r_1) + q_2V(r_2) + U_{12}$; the mutual interaction is counted once.

Step 1: (a) Find the initial mutual energy The charges lie on opposite sides of the origin. Their separation is therefore $r_{12} = 6 - (-4) = 10 \text{ cm} = 0.10 \text{ m}$. Substituting the charges in coulombs,

$$U_i = \frac{(9 \times 10^9)(-5 \times 10^{-6})(2 \times 10^{-6})}{0.10} = -0.90 \text{ J}.$$

The negative sign indicates attraction and a bound configuration relative to infinite separation.

Step 2: (a) Calculate the separating work At infinite separation, $U_f = 0$. Hence an external agent must supply energy against the attractive electric force:

$$W_{\text{ext}} = 0 - (-0.90) = +0.90 \text{ J}.$$

The work done by the electric force itself is the negative of this quantity.

Step 3: (b) Evaluate the external-field contributions Interpret the given inverse-square field as radial about the origin. With the potential zero at infinity,

$$V(r) = - \int_{\infty}^r \frac{A}{s^2} ds = \frac{A}{r}.$$

Distances from the origin are positive: $r_1 = 0.04 \text{ m}$ and $r_2 = 0.06 \text{ m}$. Thus

$$\begin{aligned} q_1V(r_1) &= \frac{(-5 \times 10^{-6})(8 \times 10^4)}{0.04} = -10 \text{ J}, \\ q_2V(r_2) &= \frac{(2 \times 10^{-6})(8 \times 10^4)}{0.06} = \frac{8}{3} \text{ J}. \end{aligned}$$

Add these to the mutual energy; the external field does not replace the interaction between the two

charges:

$$U = -10 + \frac{8}{3} - 0.90 = -\frac{247}{30} \text{ J}.$$

Step 4: Conclusion (a) The work required to separate the charges is $+0.90 \text{ J}$. (b) The initial total electrostatic potential energy in the given external field is -8.23 J , with zero potential at infinity.

Quick Tip to Solve: Use the separation 0.10 m for mutual energy, but the individual distances 0.04 m and 0.06 m for external potentials.

Section D (8 marks)

Questions number 29 and 30 are case study-based questions. Read the following paragraphs and answer the questions that follow.

29. When light travels from an optically denser medium to an optically rarer medium, at the interface it is partly reflected back into the same medium and partly refracted to the second medium. The angle of incidence corresponding to an angle of refraction 90° is called the critical angle (i_c) for the given pair of media. This angle is related to the refractive index of medium 1 with respect to medium 2. Refraction of light through a prism involves refraction at two plane interfaces. A relation for the refractive index of the material of the prism can be obtained in terms of the refracting angle of the prism and the angle of minimum deviation. For a thin prism, this relation reduces to a simple equation. Laws of refraction are also valid for refraction of light at a spherical interface. When an object is placed in front of a spherical surface separating two media, its image is formed. A relation between object and image distance, in terms of refractive indices of two media and the radius of curvature of the spherical surface can be obtained. Using this relation for two surfaces of a lens, 'lens maker formula' is obtained. [4 marks]

29(i). (i) A small bulb is placed at the bottom of a tank containing a transparent liquid (refractive index n) to a depth H . The radius of the circular area of the surface of liquid, through which light from the bulb can emerge out, is R . Then $\left(\frac{R}{H}\right)$ is: [1 mark]

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

Correct Answer: (A) $\frac{1}{\sqrt{n^2 - 1}}$

Solution:

Concept:

- For light emerging from a liquid of refractive index n into air, the critical angle satisfies $\sin i_c = 1/n$.

- The limiting emergent ray forms a right triangle with liquid depth H and surface radius R , so $R/H = \tan i_c$.

Step 1: Identify the boundary of the emerging light Rays incident below the critical angle emerge into air; rays above it undergo total internal reflection. At the circular boundary the incidence angle is i_c , measured from the vertical normal, giving $R = H \tan i_c$.

Step 2: Express the tangent in terms of refractive index Use $\cos i_c = \sqrt{1 - 1/n^2}$. Then

$$\frac{R}{H} = \frac{\sin i_c}{\cos i_c} = \frac{1/n}{\sqrt{1 - 1/n^2}} = \frac{1}{\sqrt{n^2 - 1}}.$$

Option (B) gives the reciprocal ratio. Options (C) and (D) incorrectly use a plus sign inside the square root, contrary to $\cos^2 i_c = 1 - \sin^2 i_c$.

Step 3: Conclusion $R/H = 1/\sqrt{n^2 - 1}$. Hence, the correct option is (A).

Quick Tip to Solve: The surface radius involves $\tan i_c$, whereas Snell's law supplies $\sin i_c$; convert between them before choosing an option.

29(ii)(a). A parallel beam of light is incident on a face of a prism with refracting angle 60° . The angle of minimum deviation is found to be 30° . The refractive index of the material of the prism is close to: [1 mark]

- (A) 1.3
- (B) 1.4
- (C) 1.5
- (D) 1.6

Correct Answer: (B) 1.4

Solution:

Concept:

- At minimum deviation the ray passes symmetrically through a prism: $i = e$ and $r_1 = r_2 = A/2$, where A is its refracting angle.
- The prism index relative to air is $n = \sin[(A + D_m)/2] / \sin(A/2)$, where D_m is the minimum deviation.

Step 1: Substitute the prism angles Here $A = 60^\circ$ and $D_m = 30^\circ$. The corresponding incidence angle is $i = (A + D_m)/2 = 45^\circ$, and the internal refraction angle is $r = A/2 = 30^\circ$.

Step 2: Calculate and compare the options Applying Snell's law at the first surface,

$$n = \frac{\sin 45^\circ}{\sin 30^\circ} = \frac{1/\sqrt{2}}{1/2} = \sqrt{2} \simeq 1.414.$$

The closest listed value is 1.4: its difference is about 0.014, compared with 0.114, 0.086 and 0.186 for

1.3, 1.5 and 1.6, respectively. The thin-prism approximation is inappropriate for a 60° prism.

Step 3: Conclusion The refractive index is $n \simeq 1.4$. Hence, the correct option is (B).

Quick Tip to Solve: Halve both $A + D_m$ and A before taking their sines; using the full angles changes the index.

OR

29(ii)(b). The angle of minimum deviation for a ray of light incident on a thin prism, made of crown glass ($n = 1.52$) is D_m . If the prism was made of dense flint glass ($n = 1.62$) instead of crown glass, the angle of minimum deviation will: [1 mark]

- (A) decrease by 4%
- (B) increase by 4%
- (C) decrease by 19%
- (D) increase by 19%

Correct Answer: (D) increase by 19%

Solution:

Concept:

- For a thin prism in air, minimum deviation is approximately $D_m = (n - 1)A$, where n is the refractive index and A the small refracting angle.
- For an unchanged prism angle, deviations are proportional to $n - 1$. Percentage change is calculated relative to the original deviation.

Step 1: Compare the crown and flint deviations Let D_c and D_f denote the minimum deviations for crown and dense flint glass. The prism shape is unchanged, so

$$D_c = 0.52A, \quad D_f = 0.62A, \quad \frac{D_f}{D_c} = \frac{0.62}{0.52} = \frac{31}{26}.$$

Since dense flint glass has the larger refractive index, the deviation increases; both decreasing options are excluded.

Step 2: Find the percentage increase Measure the increase using crown glass as the reference:

$$\frac{D_f - D_c}{D_c} \times 100 = \frac{0.62 - 0.52}{0.52} \times 100 \simeq 19.23\%.$$

This is close to 19%, not 4%. Comparing the indices themselves instead of their excess above unity would use the wrong proportionality.

Step 3: Conclusion The minimum deviation increases by approximately 19% . Hence, the correct option is (D).

Quick Tip to Solve: For the same thin prism, compare $n - 1$, then divide the change by the original $n - 1 = 0.52$.

29(iii). (iii) An object is placed in front of a convex spherical glass surface ($n = 1.5$ and radius of curvature R) at a distance of $4R$ from it. As the object is moved slowly close to the surface, the image formed is: [1 mark]

- (A) always real
- (B) always virtual
- (C) first real and then virtual
- (D) first virtual and then real

Correct Answer: (C) first real and then virtual

Solution:

Concept:

- Refraction at a spherical interface obeys $n_2/v - n_1/u = (n_2 - n_1)/R$, using Cartesian signs along the incident light.
- For an object in air facing convex glass, $n_1 = 1$, $n_2 = 1.5$, $u = -d$ with $d > 0$, and the centre of curvature lies in glass, so $R > 0$.

Step 1: Express the image position using the object distance Substitute the indices and signs into the surface formula:

$$\frac{1.5}{v} + \frac{1}{d} = \frac{0.5}{R}, \quad v = \frac{3Rd}{d - 2R}.$$

At the starting distance $d = 4R$, this gives $v = 6R > 0$. The refracted rays actually meet in glass, so the initial image is real.

Step 2: Follow the image as the object approaches As d decreases toward $2R$ from above, the positive image distance increases without bound. At $d = 2R$, refracted rays are parallel. For $0 < d < 2R$, the denominator becomes negative and $v < 0$, giving a virtual image on the object side. Thus neither “always real” nor “always virtual” is correct; the reverse sequence also contradicts the real image at $4R$.

Step 3: Conclusion The image is first real and then virtual. Hence, the correct option is (C).

Quick Tip to Solve: Find where $1/v = 0$: here $d = 2R$ separates the real-image and virtual-image regimes.

29(iv). (iv) A double-convex lens, made of glass of refractive index 1.5, has focal length 10 cm. The radius of curvature of its each face, is: [1 mark]

- (A) 10 cm
- (B) 15 cm
- (C) 20 cm
- (D) 40 cm

Correct Answer: (A) 10 cm

Solution:

Concept:

- For a thin lens in air, the lens maker's formula is $1/f = (n - 1)(1/R_1 - 1/R_2)$, where n is the lens refractive index.
- For a symmetric double-convex lens, the two radii have equal magnitude R and opposite Cartesian signs: $R_1 = +R$, $R_2 = -R$.

Step 1: Account for both curved faces The reference to the radius of each face implies equal curvatures. Substituting their signed radii,

$$\frac{1}{f} = (n - 1) \left(\frac{1}{R} - \frac{1}{-R} \right) = \frac{2(n - 1)}{R}.$$

The contributions add because the second radius is negative. Giving both radii the same sign would incorrectly cancel the lens power.

Step 2: Substitute the index and focal length Rearranging for the radius magnitude and using centimetres consistently,

$$R = 2(n - 1)f = 2(1.5 - 1)(10 \text{ cm}) = 10 \text{ cm}.$$

Options 15, 20 and 40 cm do not satisfy the relation; with $n = 1.5$, the factor $2(n - 1)$ is exactly unity, so the radius equals the focal length.

Step 3: Conclusion The radius of curvature of each face has magnitude 10 cm. Hence, the correct option is (A).

Quick Tip to Solve: For an equiconvex glass lens with $n = 1.5$, remember $R = f$; retain opposite signs for the two surface radii.

30. In a metallic conductor, an electron, moving due to thermal motion, suffers collisions with the heavy fixed ions but after collision, it will emerge out with the same speed but in random directions. If we consider all the electrons, their average velocity will be zero. When an electric field is applied, electrons move with an average velocity, known as drift velocity (v_d). The average time between successive collisions is known as relaxation time (τ). The magnitude of drift velocity per unit electric field is called mobility (μ). An expression for current through the conductor can be obtained in terms of drift velocity, number of electrons per unit volume (n), electronic charge ($-e$), and the cross-sectional area (A) of the conductor. This expression leads to an expression between current density ($\vec{J}$) and the electric field ($\vec{E}$). Hence, an expression for resistivity (ρ) of a metal is obtained. This expression helps us to understand increase in resistivity of a metal with increase in its temperature, in terms of change in the relaxation time (τ) and change in the number density of electrons (n). [4 marks]

30(i). (i) Consider two cylindrical conductors A and B , made of the same metal connected in series to a battery. The length and the radius of B are twice that of A . If μ_A and μ_B are the mobility of electrons in A and B respectively, then $\frac{\mu_A}{\mu_B}$ is: [1 mark]

- (A) $\frac{1}{2}$
- (B) $\frac{1}{4}$
- (C) 2
- (D) 1

Correct Answer: (D) 1

Solution:

Concept:

- Electron mobility is $\mu = v_d/E = e\tau/m$, where v_d is drift speed, E is electric field, τ is relaxation time and m is electron mass.
- For the same metal at the same temperature, mobility is a material property independent of the conductor's length and cross-sectional area.

Step 1: Compare the microscopic material properties Both conductors are made of the same metal, so their electrons have the same relaxation time under the stated conditions. Their dimensions affect resistance, but do not change $e\tau/m$. Thus $\mu_A = \mu_B$.

Step 2: Check why the geometrical ratios do not apply The series current is the same in both wires. Since $r_B = 2r_A$, their areas obey $S_B = 4S_A$, so $v_{d,B} = v_{d,A}/4$. The field also obeys $E_B = E_A/4$ because $E = \rho I/S$. Therefore the ratio v_d/E remains unchanged. Options (A), (B) and (C) confuse dimensions, drift speed or resistance with mobility.

Step 3: Conclusion

$$\frac{\mu_A}{\mu_B} = 1.$$

Hence, the correct option is (D).

Quick Tip to Solve: Before using a wire's dimensions, check whether the requested quantity is a material property: mobility depends on relaxation time, not geometry.

30(ii). (ii) A wire of length 0.5 m and cross-sectional area $1.0 \times 10^{-7} \text{ m}^2$ is connected to a battery of 2 V that maintains a current of 1.5 A in it. The conductivity of the material of the wire (in $\Omega^{-1} \text{ m}^{-1}$) is: [1 mark]

- (A) 2.5×10^4
- (B) 3.0×10^5
- (C) 3.75×10^6
- (D) 5.0×10^7

Correct Answer: (C) 3.75×10^6

Solution:

Concept:

- For a uniform wire, resistance is $R = \rho L/A$, where ρ is resistivity, L is length and A is cross-sectional area.
- Conductivity is $\sigma = 1/\rho$; using Ohm's law $R = V/I$ gives $\sigma = IL/(VA)$.

Step 1: Determine the resistance The applied voltage and steady current give

$$R = \frac{V}{I} = \frac{2}{1.5} = \frac{4}{3} \Omega.$$

The resistance alone does not give conductivity; the length and cross-sectional area must also be included.

Step 2: Use the wire dimensions to calculate conductivity Substitute $L = 0.5 \text{ m}$ and $A = 1.0 \times 10^{-7} \text{ m}^2$:

$$\sigma = \frac{IL}{VA} = \frac{1.5 \times 0.5}{2 \times 1.0 \times 10^{-7}} = 3.75 \times 10^6 \Omega^{-1} \text{ m}^{-1}.$$

Option (C) agrees with both the coefficient and power of ten. Options (A), (B) and (D) fail the numerical substitution; the inverse of this result would instead be resistivity.

Step 3: Conclusion The conductivity is $3.75 \times 10^6 \Omega^{-1} \text{ m}^{-1}$. Hence, the correct option is (C).

Quick Tip to Solve: Combine Ohm's law and wire resistance directly as $\sigma = IL/(VA)$, keeping the area exponent in the denominator.

30(iii). (iii) The temperature coefficient of resistance of nichrome is $1.70 \times 10^{-4} \text{ }^\circ\text{C}^{-1}$. In order to increase resistance of a nichrome wire by 8.5%, the temperature of the wire should be increased by: [1 mark]

- (A) 250°C
- (B) 500°C
- (C) 850°C
- (D) 1000°C

Correct Answer: (B) 500°C

Solution:

Concept:

- With constant temperature coefficient α , resistance follows $R = R_0(1 + \alpha\Delta T)$, where R_0 is the initial resistance and ΔT is the temperature rise.
- The fractional increase is $\Delta R/R_0 = \alpha\Delta T$; a percentage must be divided by 100 before substitution.

Step 1: Convert the increase to a fraction An increase of 8.5% means

$$\frac{\Delta R}{R_0} = \frac{8.5}{100} = 0.085.$$

The temperature coefficient is $\alpha = 1.70 \times 10^{-4} \text{ }^\circ\text{C}^{-1}$, so the unknown initial resistance cancels from the calculation.

Step 2: Calculate and check the temperature rise Rearranging the fractional-change relation,

$$\Delta T = \frac{0.085}{1.70 \times 10^{-4}} = 500 \text{ }^\circ\text{C}.$$

This gives exactly 8.5%. By comparison, rises of 250 , 850 and $1000 \text{ }^\circ\text{C}$ would give increases of 4.25%, 14.45% and 17%, so options (A), (C) and (D) do not satisfy the question.

Step 3: Conclusion The required temperature increase is $500 \text{ }^\circ\text{C}$. Hence, the correct option is (B).

Quick Tip to Solve: Use $\Delta T = (\text{percentage increase})/(100\alpha)$; substituting 8.5 instead of 0.085 produces a hundredfold error.

30(iv)(a). Consider the contribution of the following two factors I and II in resistivity of a metal:

I. Relaxation time of electrons

II. Number of electrons per unit volume

The resistivity of a metal increases with increase in its temperature because:

[1 mark]

- (A) I decreases and II increases.
- (B) I increases and II is almost constant.
- (C) Both I and II increase.
- (D) I decreases and II is almost constant.

Correct Answer: (D) I decreases and II is almost constant.

Solution:

Concept:

- The resistivity of a metal is $\rho = m/(ne^2\tau)$, where n is the number of conduction electrons per unit volume and τ is their relaxation time.
- Relaxation time is the average interval between successive collisions; more frequent scattering reduces τ and hence increases resistivity.

Step 1: Determine the effect on relaxation time Heating a metal increases the vibrations of its lattice ions. The conduction electrons scatter more frequently, so their average time between collisions decreases. Therefore factor I, the relaxation time, decreases.

Step 2: Determine the effect on electron number density Metals already contain a large number of free conduction electrons. Over the temperature range described by the metallic conduction model, their number density n remains almost constant. Thus factor II is almost constant and the fall in τ raises ρ . Option (A) incorrectly requires n to increase, while (B) and (C) incorrectly require the relaxation time to increase.

Step 3: Conclusion I decreases and II is almost constant. Hence, the correct option is (D).

Quick Tip to Solve: Remember $\rho \propto 1/\tau$ for a metal with nearly fixed carrier density: heating increases scattering and reduces relaxation time.

30(iv)(b). A steady current flows in a copper wire of non-uniform cross-section. Consider the following three physical quantities:

I. Electric field

II. Current density

III. Drift speed

Then at the different points along the wire:

[1 mark]

(A) II and III change, but I is constant.

(B) I and II change, but III is constant.

(C) I and III change, but II is constant.

(D) All I, II and III change.

Correct Answer: (D) All I, II and III change.

Solution:

Concept:

- Charge conservation makes steady current I the same through every cross-section, whereas current density is $J = I/A$, with A the local area.
- Drift speed is $v_d = J/(ne)$ and electric field is $E = \rho J$, where n is carrier density and ρ is resistivity.

Step 1: Compare current density and drift speed Area changes along the wire but current remains constant. Thus $J = I/A$ is greater in narrower portions. For the same copper, n is constant, so $v_d = I/(neA)$ also varies inversely with area. Quantities II and III both change.

Step 2: Apply the local form of Ohm's law The copper has uniform resistivity under the stated conditions, so

$$E = \rho J = \frac{\rho I}{A}.$$

The field also increases in narrower portions. Option (A) incorrectly keeps the field constant, (B) keeps drift speed constant, and (C) keeps current density constant. Each contradicts its respective relation to area.

Step 3: Conclusion All I, II and III change along the wire. Hence, the correct option is (D).

Quick Tip to Solve: Hold current fixed and track $1/A$: current density, drift speed and electric field all follow it.

Section E (15 marks)

31(a). (i) Explain with the help of a labelled ray diagram the formation of final image by an astronomical telescope at infinity. Write the expression for its magnifying power.

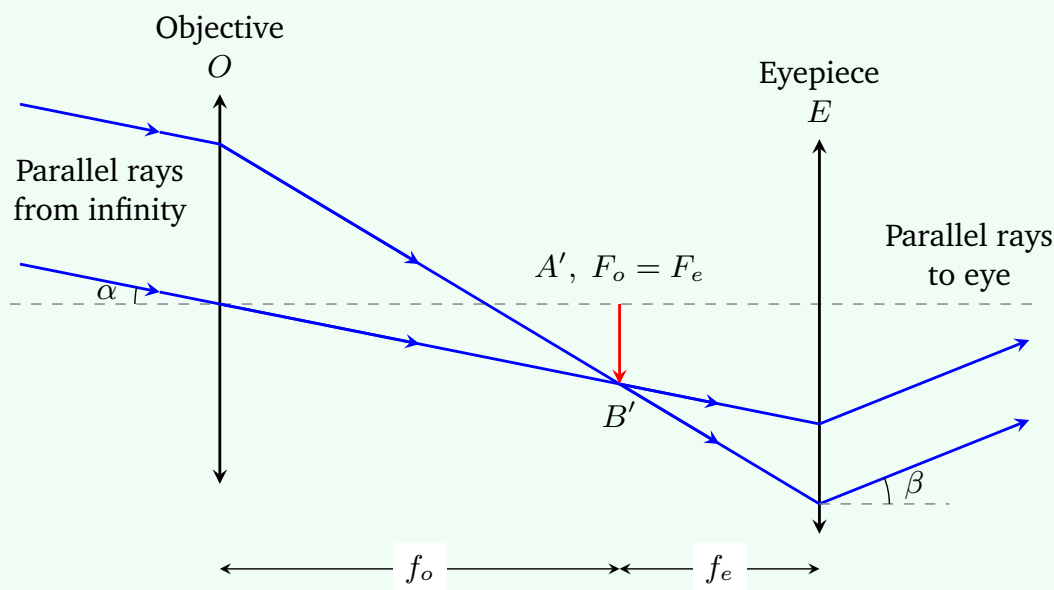
(ii) The total magnification produced by a compound microscope is 20. The magnification produced by the eyepiece is 5. When the microscope is focussed on a certain object, the distance between the objective and eyepiece is observed to be 14 cm. Calculate the focal lengths of the objective and the eyepiece. (Given that the least distance of distinct vision = 25 cm) [5 marks]

Solution:

Concept:

- An astronomical telescope in normal adjustment has the objective's second focal plane coincident with the eyepiece's first focal plane. The final image is at infinity.
- Angular magnifying power is $M = \beta/\alpha$. For a telescope, $M = -f_o/f_e$, where f_o and f_e are the objective and eyepiece focal lengths.
- For a compound microscope, the magnitude of total magnification is $|m| = |m_o|m_e$. With the final image at the near point, $m_e = 1 + D/f_e$, where D is the least distance of distinct vision.
- For each thin lens, $1/f = 1/v - 1/u$, with Cartesian signs; the objective's linear magnification is $m_o = v_o/u_o$.

Step 1: (i) Form the telescope's intermediate and final images The objective is a convex lens of large aperture and long focal length. Parallel rays from a distant object enter the objective and form a real, inverted, diminished image $A'B'$ in its focal plane. Place the convex eyepiece so that this image also lies in the eyepiece's first focal plane. Rays from each point of $A'B'$ then emerge parallel after refraction through the eyepiece. Thus the final image is virtual, inverted relative to the distant object, and at infinity; the eye observes it without accommodation. The lens separation in this normal adjustment is $f_o + f_e$. The diagram follows the rays from one off-axis point of the distant object.



Astronomical telescope in normal adjustment: F_o and F_e coincide; the emerging rays are parallel.

Step 2: (i) Obtain the angular magnifying power Let the intermediate image have height magnitude h . The small angle subtended by the distant object at the objective has magnitude $|\alpha| \simeq h/f_o$; the angle subtended by the final image at the eye has magnitude $|\beta| \simeq h/f_e$. Hence

$$|M| = \frac{|\beta|}{|\alpha|} = \frac{h/f_e}{h/f_o} = \frac{f_o}{f_e}.$$

The image is inverted, so the signed angular magnification is $M = -f_o/f_e$. A long-focal-length objective and short-focal-length eyepiece therefore provide a large angular magnification.

Step 3: (ii) Find the objective magnification and eyepiece focal length The given magnifications are magnitudes. The objective produces an inverted intermediate image, so

$$|m_o| = \frac{20}{5} = 4, \quad m_o = -4.$$

Using the usual near-point viewing condition for the microscope, the final image is at $v_e = -D = -25$ cm. Then

$$5 = 1 + \frac{25}{f_e} \Rightarrow f_e = \frac{25}{4} = 6.25 \text{ cm}.$$

Apply the lens formula to the eyepiece:

$$\begin{aligned} \frac{1}{6.25} &= \frac{1}{-25} - \frac{1}{u_e}, \\ \frac{1}{u_e} &= -\frac{1}{25} - \frac{4}{25} = -\frac{1}{5}. \end{aligned}$$

Thus the intermediate image is 5 cm to the left of the eyepiece.

Step 4: (ii) Use the lens separation to determine the objective focal length The distance between the

lenses is 14 cm. The real intermediate image therefore lies to the right of the objective at

$$v_o = 14 - 5 = 9 \text{ cm.}$$

Since $v_o/u_o = -4$, the object distance is $u_o = -9/4 = -2.25 \text{ cm}$. Applying the lens formula gives

$$\begin{aligned}\frac{1}{f_o} &= \frac{1}{9} - \frac{1}{-2.25} \\ &= \frac{1}{9} + \frac{4}{9} = \frac{5}{9} \text{ cm}^{-1}, \\ f_o &= \frac{9}{5} = 1.8 \text{ cm.}\end{aligned}$$

The signs are consistent: a real object beyond the objective's focal point forms a real inverted intermediate image.

Step 5: State the viewing condition used in the numerical result The printed microscope question does not explicitly specify the final-image position. The near-point convention used above gives $f_e = 6.25 \text{ cm}$. If the microscope instead has its final image at infinity, then $m_e = D/f_e$ gives $f_e = 5 \text{ cm}$; the intermediate image is again 5 cm before the eyepiece and $f_o = 1.8 \text{ cm}$ remains unchanged. Thus the stated eyepiece result uses the near-point assumption explicitly.

Step 6: Conclusion (i) For the telescope in normal adjustment, $M = -f_o/f_e$, and its length is $f_o + f_e$. (ii) With the microscope's final image at the near point, $f_o = 1.8 \text{ cm}$, $f_e = 6.25 \text{ cm}$. For a final image at infinity, the alternative eyepiece focal length is 5 cm.

Quick Tip to Solve: Divide total microscope magnification by eyepiece magnification first. Subtract the intermediate image's distance from the eyepiece from the lens separation to obtain the objective image distance.

OR

31(b). (i) Two coherent light waves, each of intensity I_0 superpose each other and produce interference pattern on a screen. Obtain the expression for the resultant intensity at a point where the phase difference between the waves is ϕ . Write its maximum and minimum possible values.

(ii) In a single slit diffraction experiment, the aperture of the slit is 3 mm and the separation between the slit and the screen is 1.5 m. A monochromatic light of wavelength 600 nm is normally incident on the slit. Calculate the distance of (I) first order minimum, and (II) second order maximum, from the centre of the screen. [5 marks]

Solution:

Concept:

- Coherent waves maintain a constant phase difference. For waves of the same polarisation, their electric-field amplitudes add; intensity is proportional to the time average of the squared resultant field.
- For a slit of width a , diffraction minima obey $a \sin \theta = n\lambda$. On a distant screen at separation D , the small-angle relation is $y \simeq D \sin \theta$.
- Secondary maxima lie approximately midway between successive minima: $a \sin \theta \simeq (n + \frac{1}{2})\lambda$, where $n = 1, 2, \dots$ counts maxima outside the central maximum.

Step 1: (i) Superpose the electric fields Let the two waves at the chosen point be $E_1 = E_0 \cos \omega t$ and

$E_2 = E_0 \cos(\omega t + \phi)$, with equal amplitude E_0 . The trigonometric sum identity gives

$$E = E_1 + E_2 = 2E_0 \cos \frac{\phi}{2} \cos \left(\omega t + \frac{\phi}{2} \right).$$

Therefore, the resultant amplitude has magnitude $2E_0 |\cos(\phi/2)|$. Since each separate wave has intensity I_0 , the ratio of intensities is the ratio of squared amplitudes:

$$\frac{I}{I_0} = \frac{4E_0^2 \cos^2(\phi/2)}{E_0^2}, \quad I = 4I_0 \cos^2 \frac{\phi}{2} = 2I_0(1 + \cos \phi).$$

Step 2: (i) Determine the limiting intensities At constructive interference, $\phi = 2m\pi$, so $\cos^2(\phi/2) = 1$ and $I_{\max} = 4I_0$. At destructive interference, $\phi = (2m + 1)\pi$, so $\cos^2(\phi/2) = 0$ and $I_{\min} = 0$, where m is any integer. Complete cancellation is possible because the two waves have equal amplitudes. The interference pattern redistributes the incident energy between bright and dark regions.

Step 3: (ii) Calculate the diffraction length scale Convert all the data to SI units:

$$a = 3 \times 10^{-3} \text{ m}, \quad D = 1.5 \text{ m}, \quad \lambda = 600 \times 10^{-9} \text{ m}.$$

The common length scale on the screen is

$$\frac{D\lambda}{a} = \frac{1.5 \times 600 \times 10^{-9}}{3 \times 10^{-3}} = 3.0 \times 10^{-4} \text{ m} = 0.30 \text{ mm}.$$

These displacements are much smaller than D , which justifies the small-angle approximation.

Step 4: (ii) Locate the first minimum and second secondary maximum For the first minimum, $n = 1$, giving

$$y_{\min,1} = \frac{D\lambda}{a} = 0.30 \text{ mm}.$$

The second secondary maximum lies between the second and third minima. Using the usual school-level approximation for its position,

$$y_{\max,2} \simeq \frac{5D\lambda}{2a} = \frac{5}{2}(0.30 \text{ mm}) = 0.75 \text{ mm}.$$

This maximum position is approximate: actual secondary maxima are slightly displaced from the midpoints between minima. The same distances occur on either side of the central maximum.

Step 5: Conclusion (i) $I = 4I_0 \cos^2(\phi/2)$, with $I_{\max} = 4I_0$ and $I_{\min} = 0$. (ii) The first minimum is 0.30 mm from the centre, and the second secondary maximum is approximately 0.75 mm from the centre.

Quick Tip to Solve: Calculate $D\lambda/a$ once. Multiply it by 1 for the first minimum and by 5/2 for the approximate second secondary maximum; do not count the central maximum as the first secondary maximum.

32(a). (i) A parallel plate capacitor with plate area A and plate separation d has a capacitance C_0 . A slab of dielectric constant K having area A and thickness $\left(\frac{d}{4}\right)$ is inserted in the capacitor, parallel to the plates. Find the new value of its capacitance.

(ii) You are provided with a large number of $1\ \mu\text{F}$ identical capacitors and a power supply of $1200\ \text{V}$. The dielectric medium used in each capacitor can withstand up to $200\ \text{V}$ only. Find the minimum number of capacitors and their arrangement, required to build a capacitor system of equivalent capacitance of $2\ \mu\text{F}$ for use with this supply. [5 marks]

Solution:

Concept:

- For parallel plates with air between them, $C_0 = \epsilon_0 A/d$, where A is the plate area and d is their separation. Fringing fields are neglected.
- A dielectric layer of thickness t and relative permittivity K , covering the entire plate area, is in series with the remaining air layer. Thus $C = \epsilon_0 A/(d - t + t/K)$.
- For n identical capacitors of capacitance c in series, $C_s = c/n$, and the applied voltage divides equally. The capacitances of parallel branches add.

Step 1: (i) Calculate the potential drop across the two media The printed slab thickness is $t = d/4$, so the total remaining air thickness is $d - t = 3d/4$. If the free charge on each plate has magnitude Q , then the electric fields in the air and the dielectric are respectively

$$E_{\text{air}} = \frac{Q}{\epsilon_0 A}, \quad E_{\text{slab}} = \frac{Q}{K\epsilon_0 A}.$$

The total potential difference is the sum of the potential drops across the air and the slab, whether the air is on one side or both sides of the slab:

$$V = \frac{Q}{\epsilon_0 A} \frac{3d}{4} + \frac{Q}{K\epsilon_0 A} \frac{d}{4} = \frac{Qd}{4\epsilon_0 A} \left(3 + \frac{1}{K}\right).$$

Step 2: (i) Express the new capacitance in terms of the original value Using $C = Q/V$,

$$C = \frac{4\epsilon_0 A}{d(3 + 1/K)} = \frac{4K}{3K + 1} \frac{\epsilon_0 A}{d} = \frac{4K}{3K + 1} C_0.$$

For $K = 1$, the expression correctly reduces to C_0 . Even for very large K , the remaining air gap limits the capacitance to $4C_0/3$.

Step 3: (ii) Determine the number in each series branch Each capacitor has capacitance $c = 1\ \mu\text{F}$ and can withstand at most $200\ \text{V}$. For n identical capacitors in series across the $1200\ \text{V}$ supply, each experiences $1200/n$ volts. Therefore,

$$\frac{1200}{n} \leq 200 \quad \Rightarrow \quad n \geq 6.$$

Use six in each branch. The branch capacitance is then $C_s = 1/6\ \mu\text{F}$, and the voltage across every capacitor is exactly $200\ \text{V}$.

Step 4: (ii) Determine the parallel branches and verify minimality With m such branches in parallel, the required equivalent capacitance gives

$$C_{\text{eq}} = \frac{m}{6} \mu\text{F} = 2\ \mu\text{F} \quad \Rightarrow \quad m = 12.$$

Thus the total number is $N = 6 \times 12 = 72$. More capacitors per series branch would reduce its capacitance and require more parallel branches. A general lower bound follows from energy: each capacitor can store at most $\frac{1}{2}c(200)^2$, whereas the required system stores $\frac{1}{2}C_{\text{eq}}(1200)^2$. Hence

$$N \geq \frac{C_{\text{eq}}(1200)^2}{c(200)^2} = 2 \times 6^2 = 72.$$

The proposed arrangement attains this bound, so its capacitor count is minimal.

Step 5: Conclusion (i) The new capacitance is $C = \frac{4K}{3K+1}C_0$. (ii) The minimum is 72 capacitors: connect 12 parallel branches, each containing 6 capacitors in series. The equivalent capacitance is $2 \mu\text{F}$, and each capacitor has 200 V across it.

Quick Tip to Solve: For a full-area dielectric slab, add air thickness and dielectric thickness divided by K . For a capacitor bank, first satisfy the voltage limit using series capacitors, then obtain the target capacitance using parallel branches.

OR

32(b). (i) An electric dipole of dipole moment $\vec{p}$ consists of point charges q and $-q$, separated by $2a$. Derive an expression for electric potential in terms of its dipole moment at a point at a distance x ($\gg a$) from its centre and lying (I) along its axis, and (II) along its bisector line.

(ii) An electric dipole of dipole moment $\vec{p} = (0.8\hat{i} + 0.6\hat{j}) \times 10^{-29} \text{ C m}$ is placed in an electric field $\vec{E} = 1.0 \times 10^7 \hat{k} \text{ V/m}$. Calculate the magnitude of the torque acting on it and the angle it makes with the x -axis, at this instant. [5 marks]

Solution:

Concept:

- Electric potential is a scalar: the potential of point charges is $V = (4\pi\epsilon_0)^{-1} \sum_i q_i/r_i$, taking zero potential at infinity.
- The electric dipole moment has magnitude $p = q(2a)$ and points from $-q$ to $+q$. On the perpendicular bisector, the distances from the two charges are equal.
- In a uniform electric field, the torque on a dipole is $\vec{\tau} = \vec{p} \times \vec{E}$. Its direction follows the right-hand rule, and its magnitude is $pE \sin \theta$, where θ is the angle between the dipole moment and the field.

Step 1: (i)(I) Add the potentials at an axial point Place $-q$ and $+q$ at distances a on opposite sides of the centre. Choose the axial observation point a distance $x > a$ from the centre on the side of $+q$, along $\vec{p}$. Its distances from $+q$ and $-q$ are $x - a$ and $x + a$, respectively. Including the sign of each charge gives

$$\begin{aligned} V_{\text{axial}} &= \frac{1}{4\pi\epsilon_0} \left(\frac{q}{x-a} - \frac{q}{x+a} \right) \\ &= \frac{1}{4\pi\epsilon_0} \frac{2qa}{x^2 - a^2} = \frac{1}{4\pi\epsilon_0} \frac{p}{x^2 - a^2}. \end{aligned}$$

Since $x \gg a$, the ratio a^2/x^2 is negligible, so the denominator can be approximated by x^2 . On the opposite axial side the distances interchange and the potential has the same magnitude with a negative sign.

Step 2: (i)(II) Evaluate the potential on the bisector At a point a distance x from the centre on the

perpendicular bisector, both charges are at distance $\sqrt{x^2 + a^2}$. Their potentials therefore cancel:

$$V_{\text{bisector}} = \frac{1}{4\pi\epsilon_0} \left(\frac{q}{\sqrt{x^2 + a^2}} - \frac{q}{\sqrt{x^2 + a^2}} \right) = 0.$$

This cancellation is exact, even before making the far-field approximation. It is cancellation of scalar potentials; it does not imply that the electric field vanishes there.

Step 3: (ii) Calculate the torque vector and its magnitude The dipole moment lies in the xy -plane, whereas the field points along $+z$, so they are perpendicular. Using $\hat{i} \times \hat{k} = -\hat{j}$ and $\hat{j} \times \hat{k} = \hat{i}$,

$$\begin{aligned}\vec{\tau} &= [(0.8\hat{i} + 0.6\hat{j}) \times 10^{-29}] \times [1.0 \times 10^7 \hat{k}] \\ &= (0.6\hat{i} - 0.8\hat{j}) \times 10^{-22} \text{ N m}, \\ |\vec{\tau}| &= \sqrt{0.6^2 + (-0.8)^2} \times 10^{-22} \text{ N m}.\end{aligned}$$

The cross product is in the xy -plane and has a positive x -component and a negative y -component.

Step 4: Find the angle of the torque with the positive x -axis If α is the angle between the torque vector and the positive x -axis, its direction cosine is

$$\cos \alpha = \frac{\tau_x}{|\vec{\tau}|} = \frac{0.6 \times 10^{-22}}{1.0 \times 10^{-22}} = 0.6, \quad \alpha = \cos^{-1}(0.6) = 53.13^\circ.$$

Because $\tau_y < 0$, the vector lies below the positive x -axis, toward the negative y -axis. Thus the angle is measured clockwise in the xy -plane; its counterclockwise polar angle would be 306.87° .

Step 5: Conclusion (i) For $x \gg a$, $V_{\text{axial}} = p/(4\pi\epsilon_0 x^2)$ on the side along $\vec{p}$, with the negative value on the opposite axial side, and $V_{\text{bisector}} = 0$. (ii) The torque is $(0.6\hat{i} - 0.8\hat{j}) \times 10^{-22} \text{ N m}$, of magnitude $1.0 \times 10^{-22} \text{ N m}$, making 53.13° clockwise from the positive x -axis.

Quick Tip to Solve: For dipole potential, add signed scalar contributions before approximating. For the torque angle, compute the cross product first and use both component signs to identify the quadrant.

33(a). (i) With the help of a labelled diagram, explain the principle of working of a moving coil galvanometer. Write the purpose of using (i) radial magnetic field, and (ii) soft iron core, in it.

(ii) Define current sensitivity of a galvanometer. "Increasing the current sensitivity may not necessarily increase the voltage sensitivity." Give reason. [5 marks]

Solution:

Concept:

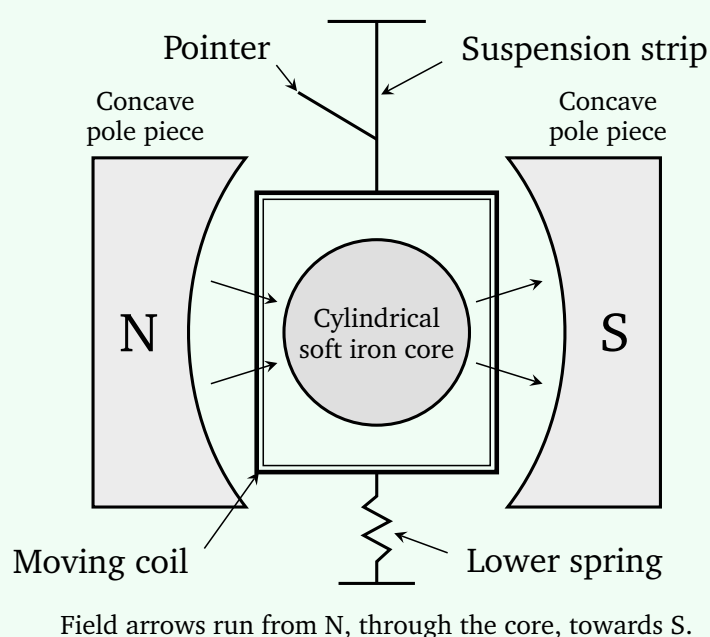
- A current-carrying coil in a magnetic field experiences a torque. For a coil of N turns and area A , $\tau_m = NIAB \sin \alpha$, where α is the angle between the coil's normal and the magnetic field B .
- A radial magnetic field keeps the coil's plane parallel to the local field, so $\alpha = 90^\circ$. A suspension strip or spring supplies the opposing restoring torque $\tau_r = k\theta$, where k is the torsional constant and θ is the angular deflection.

- Current sensitivity is deflection per unit current, $S_I = \theta/I$. Voltage sensitivity is deflection per unit applied potential difference, $S_V = \theta/V = S_I/G$, where G is the galvanometer resistance.

Step 1: (i) Construction and working principle A light rectangular coil of many turns is suspended between the concave pole pieces of a strong permanent magnet. A cylindrical soft iron core lies inside the coil. The suspension strip and lower spring provide the current connections and the restoring torque. The coil can rotate about the suspension axis; its deflection is read using a pointer or a mirror arrangement. When current flows through the coil, the magnetic forces on its opposite vertical sides form a couple. In the radial field, their torque is $NIAB$. The coil turns until the restoring torque balances this magnetic torque:

$$NIAB = k\theta, \quad \theta = \frac{NAB}{k}I.$$

Thus the deflection is proportional to the current, for fixed N, A, B and k . Reversing the current reverses the torque and the direction of deflection.



Schematic moving coil galvanometer: concave pole pieces and a cylindrical soft iron core produce the radial field in the air gap.

Step 2: (i) Roles of the radial field and the soft iron core The concave pole faces and cylindrical core produce a radial magnetic field. As the coil rotates, its plane remains parallel to the field at its active sides. Consequently, the torque factor $\sin \alpha$ remains unity: the magnetic torque is maximum for a given current and does not decrease with deflection. This gives the linear relation $\theta \propto I$ and a uniform scale. The soft iron core has high magnetic permeability. It concentrates the magnetic flux and increases B in the air gap, increasing the torque and sensitivity. Its cylindrical shape also helps make the field radial. It is the combined pole-piece and core arrangement that maintains the required field geometry.

Step 3: (ii) Current sensitivity and its relation to voltage sensitivity The current sensitivity of a

galvanometer is its angular deflection per unit current passing through it:

$$S_I = \frac{\theta}{I} = \frac{NAB}{k}.$$

Its SI unit is rad A^{-1} . If a potential difference V is applied across the galvanometer of resistance G , then $I = V/G$, and hence

$$S_V = \frac{\theta}{V} = \frac{NAB}{kG} = \frac{S_I}{G}.$$

Increasing the number of turns increases S_I , but it also increases the wire length and therefore G . For example, with the same wire material, cross-section and approximately the same area per turn, doubling N approximately doubles both S_I and G . Their ratio, and thus S_V , stays approximately unchanged. Therefore an increase in current sensitivity does not by itself guarantee increased voltage sensitivity; the accompanying resistance change must also be considered.

Step 4: Conclusion A moving coil galvanometer works by balancing the magnetic torque $NIAB$ against the restoring torque $k\theta$. The radial field gives a uniform scale, while the soft iron core strengthens and helps radialise the field. Its sensitivities are $S_I = NAB/k$ and $S_V = S_I/G$; an increase in resistance can offset an increase in current sensitivity.

Quick Tip to Solve: For sensitivity comparisons, write both $S_I = NAB/k$ and $S_V = S_I/G$ before changing the number of turns: more turns also mean more wire resistance.

OR

33(b). (i) (I) Write Ampere's circuital law in mathematical form and explain the terms used.

(II) As the current carrying solenoid is made longer, the magnetic field produced outside it approaches zero. Why?

(III) A flexible loop of irregular shape carrying current when located in an external magnetic field, changes to a circular shape. Give reason.

(ii) A galvanometer of resistance G is converted into a voltmeter to measure up to V volts, by connecting a resistance R_1 in series with the coil. If R_1 is replaced by R_2 , then it can only measure up to $\frac{V}{2}$ volt. Find the value of the resistance R_3 (in terms of R_1 and R_2) needed to convert it into a voltmeter that can read up to $2V$.

[5 marks]

Solution:

Concept:

- Ampere's circuital law relates the circulation of the magnetic field around a closed path to the net steady current enclosed by that path.
- A current element in an external magnetic field experiences $d\vec{F} = I d\vec{l} \times \vec{B}$. A planar loop has magnetic moment $\vec{m} = I\vec{A}$ and potential energy $U = -\vec{m} \cdot \vec{B}$.
- A galvanometer becomes a voltmeter when a high resistance is connected in series. Its full-scale voltage is $V_{fs} = I_g(G + R)$, where I_g is its full-scale current, G its coil resistance and R the added series resistance.

Step 1: (i)(I) State Ampere's circuital law For steady currents in free space, the line integral of the

magnetic field along a closed path is

$$\oint_C \vec{B} \cdot d\vec{l} = \mu_0 I_{\text{enc}}.$$

Here $\vec{B}$ is the magnetic field at the path element, $d\vec{l}$ is the directed infinitesimal length along the closed path C , μ_0 is the permeability of free space, and I_{enc} is the algebraic sum of currents passing through a surface bounded by C . The positive sense of current and the direction of traversal are related by the right-hand rule.

Step 2: (i)(II) Explain the weak external field of a long solenoid The external field of a finite solenoid is mainly associated with its ends. As its length becomes much greater than its diameter, end effects become negligible in the central region. The external contributions of its many turns nearly cancel, whereas their axial fields reinforce inside. Thus the field outside, away from the ends, approaches zero in the ideal infinitely long solenoid limit. For a finite solenoid, a small fringing field still exists near either end; the statement does not imply that this end field is exactly zero.

Step 3: (i)(III) Explain why the flexible loop becomes circular In the usual uniform-field configuration, the loop tends to orient its magnetic moment along the applied field. The forces $d\vec{F} = I d\vec{l} \times \vec{B}$ on successive elements then act outward, perpendicular to the local tangent in the plane of the loop. Since the wire is flexible, these distributed forces deform it and tend to increase the enclosed area. Equivalently, with the magnetic moment aligned, $U = -IAB$, so increasing A lowers the magnetic potential energy. The wire length fixes the perimeter, and a circle encloses the greatest area for that perimeter. The loop therefore tends to become circular.

Step 4: (ii) Relate the two given voltmeter ranges The same galvanometer has the same full-scale current I_g in both arrangements. Applying Ohm's law to the series combination gives

$$V = I_g(G + R_1),$$
$$\frac{V}{2} = I_g(G + R_2).$$

Divide the first equation by the second, or multiply the second by two, to eliminate both the unknown current and the voltage:

$$G + R_1 = 2(G + R_2), \quad G = R_1 - 2R_2.$$

This relation follows from the unchanged coil resistance; the added resistance alone is not proportional to the voltage range.

Step 5: (ii) Determine the series resistance for the doubled range Let R_3 be the resistance to be connected in series to measure up to $2V$. Then

$$2V = I_g(G + R_3).$$

Comparing this equation with $V = I_g(G + R_1)$ gives

$$G + R_3 = 2(G + R_1), \quad R_3 = G + 2R_1.$$

Substitute the expression for G obtained from the two given ranges. Both the coil and the series resistor carry I_g , so doubling the range doubles their total resistance.

Step 6: Conclusion Ampere's law is $\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{\text{enc}}$. Outside a very long solenoid, the field away from the ends is negligible. A flexible current loop tends to become circular because the magnetic

forces favour maximum area for its fixed perimeter. The required series resistance is

$$R_3 = 3R_1 - 2R_2.$$

Quick Tip to Solve: For the same galvanometer, write each range as $I_g(G + R)$, then divide the range equations to eliminate I_g . Scale the total resistance, including G .