

CBSE Class 12 Physics Question Paper 2024 with Solution PDF-Set 55/3/1



Question Paper with Solutions

Conducted by the Central Board of Secondary Education (CBSE)

Time Allowed: 3 hours

Maximum Marks: 70

General Instructions

- (i) This question paper contains **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 :

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

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

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

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

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

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

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

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

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

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

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

Section A (16 marks)

1. Consider a group of charges $q_1, q_2, q_3, \dots$ such that $\Sigma q \neq 0$. Then equipotentials at a large distance, due to this group are approximately: [1 mark]

- (A) Plane
- (B) Spherical surface
- (C) Paraboloidal surface
- (D) Ellipsoidal surface

Correct Answer: (B) Spherical surface

Solution:

Concept:

- For a localized charge distribution, the far-field potential is dominated by its nonzero total charge $Q = \sum_i q_i$.
- At distance r much greater than the size of the group, $V \simeq Q/(4\pi\epsilon_0 r)$; an equipotential has constant V .

Step 1: Replace the distant group by its net charge Since $Q \neq 0$, the leading contribution behaves like the potential of a point charge. Differences between the distances from the observer to the individual charges are small compared with r , so angular corrections are negligible.

Step 2: Identify the constant-potential surface With Q fixed, constant V requires approximately constant r . Points at a fixed distance from the charge group form a sphere. Planes are characteristic of a uniform field; paraboloidal and ellipsoidal surfaces do not describe this leading, angle-independent point-charge potential.

Step 3: Conclusion The distant equipotential surfaces are approximately spherical. Hence, the correct option is (B).

Quick Tip to Solve: When the net charge is nonzero and the observation distance is large, use the point-charge potential before considering the arrangement of individual charges.

2. A proton is taken from point P_1 to point P_2 , both located in an electric field. The potentials at points P_1 and P_2 are -5 V and $+5$ V respectively. Assuming that kinetic energies of the proton at points P_1 and P_2 are zero, the work done on the proton is: [1 mark]

- (A) -1.6×10^{-18} J
- (B) 1.6×10^{-18} J
- (C) Zero
- (D) 0.8×10^{-18} J

Correct Answer: (B) 1.6×10^{-18} J

Solution:

Concept:

- The change in electric potential energy is $\Delta U = q(V_2 - V_1)$, where q is the charge transported.
- For equal initial and final kinetic energies, the work supplied by the external agent is $W_{\text{ext}} = \Delta U$; the electric field does work $W_{\text{field}} = -\Delta U$.

Step 1: Calculate the potential-energy increase A proton has positive charge $e = 1.6 \times 10^{-19}$ C. Its potential rises by $5 - (-5) = 10$ V. Thus

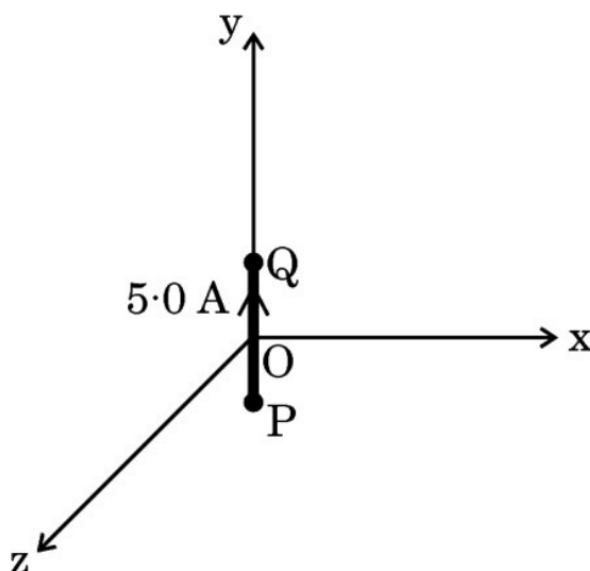
$$\Delta U = (1.6 \times 10^{-19})(10) = 1.6 \times 10^{-18} \text{ J.}$$

Step 2: Distinguish the work contributions Here the work required to take the proton between the points is the external work. The field does negative work, so option (A) gives the field contribution instead. The net work of all forces is zero because $\Delta K = 0$, but that is not the external work required; option (C) confuses these. Option (D) uses only 5 V instead of the full potential difference.

Step 3: Conclusion The required external work is $+1.6 \times 10^{-18}$ J. Hence, the correct option is (B).

Quick Tip to Solve: Subtract potentials with their signs: going from -5 V to $+5$ V is a rise of 10 V, not 5 V.

3. A 2.0 cm segment of wire, carrying 5.0 A current in positive y-direction lies along y-axis, as shown in the figure. The magnetic field at a point (3 m, 4 m, 0) due to this segment (part of a circuit) is: [1 mark]



- (A) $(0.12 \text{ nT}) \hat{j}$
- (B) $-(0.10 \text{ nT}) \hat{j}$
- (C) $-(0.24 \text{ nT}) \hat{k}$
- (D) $(0.24 \text{ nT}) \hat{k}$

Correct Answer: (C) $-(0.24 \text{ nT}) \hat{k}$

Solution:

Concept:

- For a short current segment, Biot-Savart law gives $\vec{B} \simeq (\mu_0/4\pi)I(\vec{\ell} \times \vec{r})/r^3$, where $\vec{r}$ points from the segment to the observation point.
- The direction follows the cross product, and $\mu_0/(4\pi) = 10^{-7} \text{ T m A}^{-1}$; also $1 \text{ nT} = 10^{-9} \text{ T}$.

Step 1: Form the displacement and cross product The segment length 0.020 m is very small compared with the observation distance. Taking its centre at the origin, $\vec{\ell} = 0.020\hat{j} \text{ m}$, $\vec{r} = (3\hat{i} + 4\hat{j}) \text{ m}$, and

$r = 5 \text{ m}$. Thus

$$\vec{\ell} \times \vec{r} = 0.020\hat{j} \times (3\hat{i} + 4\hat{j}) = -0.060\hat{k} \text{ m}^2.$$

Step 2: Substitute in Biot-Savart law

$$\vec{B} \simeq 10^{-7} \frac{5.0(-0.060\hat{k})}{5^3} \text{ T} = -2.4 \times 10^{-10}\hat{k} \text{ T}.$$

Options (A) and (B) incorrectly place the field along the current direction. Option (D) has the correct magnitude but reverses the cross-product direction.

Step 3: Conclusion $\vec{B} \simeq -(0.24 \text{ nT})\hat{k}$. Hence, the correct option is (C).

Quick Tip to Solve: Find $\hat{j} \times \hat{i} = -\hat{k}$ first; the direction immediately eliminates three of these four options.

4. A circular loop of wire, carrying a current I is lying in xy -plane with its centre coinciding with the origin. It is subjected to a uniform magnetic field pointing along $+z$ -axis. The loop will: [1 mark]

- (A) move along x -axis
- (B) move along $-y$ -axis
- (C) move along z -axis
- (D) remain stationary

Correct Answer: (D) remain stationary

Solution:

Concept:

- The net force on a closed current loop in a uniform magnetic field is $\vec{F} = I \oint d\vec{\ell} \times \vec{B} = \vec{0}$.
- The torque is $\vec{\tau} = \vec{M} \times \vec{B}$, where $\vec{M} = IA\hat{n}$ is the magnetic moment and $\hat{n}$ is normal to the loop.

Step 1: Check for translational motion The magnetic field is uniform, so forces on opposite elements of the circular loop cancel. Equivalently, $\oint d\vec{\ell} = \vec{0}$, giving zero resultant force. The field therefore cannot accelerate the whole loop along x , $-y$, or z , ruling out (A), (B), and (C).

Step 2: Check for rotational motion The loop lies in the xy -plane, so its magnetic moment points along $+z$ or $-z$, depending on the current direction. In either case the moment is collinear with $\vec{B}$, and $MB \sin \theta = 0$. Therefore there is no torque in the stated orientation. Individual radial forces can cause stress, but give no overall translation or rotation of the loop.

Step 3: Conclusion The loop remains stationary in its stated orientation. Hence, the correct option is (D).

Quick Tip to Solve: For a current loop, check both net force and torque: uniform field gives zero net force, while collinear moment and field give zero torque.

5. A current carrying circular loop of magnetic moment $\vec{M}$ is suspended in a vertical plane in an external magnetic field $\vec{B}$ such that its plane is normal to $\vec{B}$. The work done in rotating this loop by 45° about an axis perpendicular to $\vec{B}$ is closest to: [1 mark]

- (A) $-0.3 MB$
- (B) $0.3 MB$
- (C) $-1.7 MB$
- (D) $1.7 MB$

Correct Answer: (B) $0.3 MB$

Solution:

Concept:

- A magnetic dipole has potential energy $U = -MB \cos \theta$, where θ is the angle between $\vec{M}$ and $\vec{B}$.
- The external work in a slow rotation equals $\Delta U = MB(\cos \theta_i - \cos \theta_f)$. The magnetic moment is normal to the loop plane.

Step 1: Identify the initial and final angles For the usual stable initial orientation of the suspended loop, the moment is parallel to the field because its plane is normal to the field. Thus $\theta_i = 0^\circ$. Rotation through 45° about an axis perpendicular to the field makes $\theta_f = 45^\circ$. The angle in the energy formula is the moment-field angle, not the plane-field angle.

Step 2: Calculate the increase in potential energy

$$W_{\text{ext}} = MB \left(1 - \frac{1}{\sqrt{2}} \right) = 0.2929 MB.$$

The positive sign means work is supplied against the restoring torque. A negative value would correspond to the field doing the work in this rotation. The values near $1.7 MB$ would require a different final angle. The stated plane orientation alone also permits an antiparallel moment; the standard answer assumes the stable parallel orientation.

Step 3: Conclusion For the stable initial orientation, the work required is approximately $0.3 MB$. Hence, the correct option is (B).

Quick Tip to Solve: Use the angle between magnetic moment and field: a loop plane perpendicular to the field has its normal along the field in stable equilibrium.

6. The current in a coil of 15 mH increases uniformly from zero to 4 A in 0.004 s. The emf induced in the coil will be: [1 mark]

- (A) 22.5 V
- (B) 17.5 V
- (C) 15.0 V
- (D) 12.5 V

Correct Answer: (C) 15.0 V

Solution:

Concept:

- Self-induction obeys $\varepsilon = -L dI/dt$, where L is the self-inductance and I is the coil current.

- For a uniform current change, the induced emf magnitude is $|\varepsilon| = L\Delta I/\Delta t$. The minus sign expresses opposition to the change.

Step 1: Convert the data and find the rate of change The inductance is $L = 15 \times 10^{-3}$ H. The current rises from zero to 4 A in 0.004 s, so

$$\frac{\Delta I}{\Delta t} = \frac{4 - 0}{0.004} = 1000 \text{ A s}^{-1}.$$

Step 2: Calculate the induced emf magnitude

$$|\varepsilon| = (15 \times 10^{-3})(1000) = 15.0 \text{ V}.$$

The induced emf opposes the increasing current. Since the listed options are positive, they represent the magnitude. Options (A), (B), and (D) do not equal the given inductance times the specified current-change rate.

Step 3: Conclusion The induced emf has magnitude 15.0 V. Hence, the correct option is (C).

Quick Tip to Solve: Convert millihenries to henries before multiplying by $\Delta I/\Delta t$; do not confuse the final current with its rate of increase.

7. Consider a solenoid of length l and area of cross-section A with fixed number of turns. The self-inductance of the solenoid will increase if: [1 mark]

- (A) both l and A are increased
- (B) l is decreased and A is increased
- (C) l is increased and A is decreased
- (D) both l and A are decreased

Correct Answer: (B) l is decreased and A is increased

Solution:

Concept:

- For a long solenoid, $L = \mu N^2 A/l$, where N is its total number of turns, A its cross-sectional area, l its length, and μ the core permeability.
- With the total number of turns and core material fixed, $L \propto A/l$.

Step 1: Identify the changes that reinforce each other Increasing A increases the magnetic flux linked with the turns. Decreasing l increases the turns per unit length and hence the field produced for the same current. In the ratio A/l , these changes both increase self-inductance, as specified in option (B).

Step 2: Check the other proposed changes If both l and A increase, as in (A), the result depends on their fractional changes; an increase is not guaranteed. If l increases and A decreases, as in (C), both changes reduce L . If both decrease, as in (D), the ratio is again undetermined without their relative changes. Only (B) guarantees an increase from the given information.

Step 3: Conclusion The inductance increases when l is decreased and A is increased. Hence, the correct option is (B).

Quick Tip to Solve: Because total turns are fixed, use $L = \mu N^2 A/l$; keeping turns per unit length fixed would be a different constraint.

8. Which one of the following has the highest frequency?

[1 mark]

- (A) Infrared rays
- (B) Gamma rays
- (C) Radio waves
- (D) Microwaves

Correct Answer: (B) Gamma rays

Solution:

Concept:

- The electromagnetic spectrum is arranged by frequency; gamma rays occupy its highest-frequency region.
- In vacuum, $c = \nu\lambda$, where c is wave speed, ν frequency and λ wavelength. A shorter wavelength corresponds to a higher frequency.

Step 1: Order the given radiations The order of increasing frequency for the listed bands is radio waves, microwaves, infrared rays and gamma rays. Visible, ultraviolet and X-ray bands lie between infrared and gamma rays in the usual spectrum ordering.

Step 2: Compare the alternatives Infrared has a higher frequency than microwaves and radio waves, but still lies below gamma rays. Thus none of options (A), (C) or (D) can be the highest-frequency radiation among these choices.

Step 3: Conclusion Gamma rays have the highest frequency among the given radiations. Hence, the correct option is (B).

Quick Tip to Solve: Recall the spectrum from radio to gamma; moving toward gamma increases frequency and decreases wavelength.

9. A proton and an alpha particle having equal velocities approach a target nucleus. They come momentarily to rest and then reverse their directions. The ratio of the distance of closest approach of the proton to that of the alpha particle will be:

[1 mark]

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

Correct Answer: (B) 2

Solution:

Concept:

- At the distance of closest approach in a head-on encounter, the incident particle's initial kinetic energy becomes electrostatic potential energy.
- For a fixed target nucleus of charge Ze , $\frac{1}{2}mv^2 = kZeq/r$. Here q , m , v and r are the projectile's charge, mass, initial speed and closest distance; $k = 1/(4\pi\epsilon_0)$.

Step 1: Obtain the dependence of closest distance Rearranging the energy equation gives $r = 2kZeq/(mv^2)$. Since both particles approach the same target with equal speeds, their closest distances

are proportional to q/m , not simply to charge or mass alone.

Step 2: Substitute proton and alpha-particle properties A proton has charge e and mass m_p ; an alpha particle has charge $2e$ and mass approximately $4m_p$. Therefore,

$$\frac{r_p}{r_\alpha} = \frac{e/m_p}{2e/(4m_p)} = 2.$$

The alpha particle has four times the initial kinetic energy but only twice the charge, so it reaches half the proton's distance. The ratio $1/2$ reverses the required order; $1/4$ and 4 omit the charge difference.

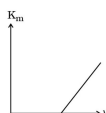
Step 3: Conclusion The ratio of the proton's closest distance to the alpha particle's closest distance is 2 . Hence, the correct option is (B).

Quick Tip to Solve: For equal incident speeds use $r \propto q/m$; for equal kinetic energies use $r \propto q$.

10. Which one of the following is the correct graph between the maximum kinetic energy (K_m) of the emitted photoelectrons and the frequency of incident radiation (ν) for a given photosensitive surface? [1 mark]



Correct Answer: (C)



Solution:

Concept:

- Einstein's photoelectric equation is $K_m = h\nu - \phi$, where h is Planck's constant and ϕ is the surface work function.
- The threshold frequency is $\nu_0 = \phi/h$; electrons are emitted only for incident frequencies at or above this threshold.

Step 1: Identify the slope and threshold Writing the equation as $K_m = h(\nu - \nu_0)$ shows a straight line of positive slope h . Its physical part starts at $K_m = 0$ at a positive frequency ν_0 , then rises as frequency increases.

Step 2: Check all four plotted alternatives Graph (A) decreases with frequency and has the wrong slope. Graph (B) has a positive energy intercept at zero frequency, incompatible with a positive work function. Graph (D) passes through the origin and would require zero work function. Graph (C) alone starts at a positive threshold frequency and rises linearly.

Step 3: Conclusion The required graph is (C), with positive slope and positive frequency-axis intercept.

Hence, the correct option is (C).

Quick Tip to Solve: For a photoelectric energy graph check two features: positive slope h and a positive threshold-frequency intercept.

11. An electron makes a transition from $n = 2$ level to $n = 1$ level in the Bohr model of a hydrogen atom. Its period of revolution: [1 mark]

- (A) increases by 87.5%
- (B) decreases by 87.5%
- (C) increases by 43.75%
- (D) decreases by 43.75%

Correct Answer: (B) decreases by 87.5%

Solution:

Concept:

- In Bohr's hydrogen model the orbital radius varies as $r_n \propto n^2$, while the electron speed varies as $v_n \propto 1/n$.
- The orbital period is $T_n = 2\pi r_n/v_n$, so $T_n \propto n^3$. Here n is the principal quantum number.

Step 1: Compare final and initial periods The electron moves from initial orbit $n = 2$ to final orbit $n = 1$. Therefore,

$$\frac{T_{\text{final}}}{T_{\text{initial}}} = \left(\frac{1}{2}\right)^3 = \frac{1}{8}.$$

The final orbit is smaller and the electron moves faster, so its revolution takes less time.

Step 2: Calculate the percentage decrease Use the initial period as the reference:

$$\frac{T_{\text{initial}} - T_{\text{final}}}{T_{\text{initial}}} \times 100\% = \left(1 - \frac{1}{8}\right) 100\% = 87.5\%.$$

Both increase options have the wrong direction. A decrease of 43.75% does not follow the cubic dependence of period on the orbit number.

Step 3: Conclusion The period of revolution decreases by 87.5%. Hence, the correct option is (B).

Quick Tip to Solve: Memorise $r_n \propto n^2$, $v_n \propto n^{-1}$, hence $T_n \propto n^3$; calculate percentage changes from the initial orbit.

12. Si is doped with a pentavalent element. The energy required to set the additional electron free is about:

[1 mark]

- (A) 0.01 eV
- (B) 0.05 eV
- (C) 0.72 eV
- (D) 1.1 eV

Correct Answer: (B) 0.05 eV

Solution:

Concept:

- A pentavalent impurity in silicon forms four covalent bonds and provides one weakly bound extra electron, producing an n-type semiconductor.
- The donor level E_D lies just below the conduction-band edge E_C . The donor ionisation energy is the small difference $E_C - E_D$.

Step 1: Identify the electron being released The additional electron is the fifth valence electron of the donor atom. Releasing it into the conduction band does not require lifting an electron across the whole silicon band gap, because its donor level already lies close to the conduction band.

Step 2: Use the donor energy scale for silicon For silicon, the typical energy needed to free this donor electron is about 0.05 eV. The smaller value 0.01 eV is the usual textbook estimate for a donor in germanium. Values near 0.72 eV and 1.1 eV are of the scale of the germanium and silicon band gaps, respectively, rather than the shallow silicon donor binding energy.

Step 3: Conclusion The required energy is approximately 0.05 eV. Hence, the correct option is (B).

Quick Tip to Solve: Distinguish the shallow donor energy from the full band gap: silicon donors need about 0.05 eV, not 1.1 eV.

13. Assertion (A): In a semiconductor, the electrons in the conduction band have lesser energy than those in the valence band.

Reason (R): Donor energy level is just above the valence band in a semiconductor.

[1 mark]

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

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

Solution:

Concept:

- A semiconductor's conduction band lies above its valence band, separated by the forbidden energy gap.
- A donor level lies just below the conduction band; an acceptor level lies just above the valence band.

Step 1: Evaluate the assertion Electrons must gain energy to move from the valence band into the conduction band. Thus electrons in the conduction band have higher energy, not lower energy, than those in the valence band. Assertion (A) is false.

Step 2: Evaluate the reason A pentavalent donor introduces an energy level close to and below the conduction-band edge. The level just above the valence band is an acceptor level associated with trivalent doping. Reason (R) confuses these two levels and is false.

Step 3: Test the explanatory link Since both statements are false, the reason cannot explain the assertion. Options (A), (B) and (C) all require a true assertion, so none describes the given statements.

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

Quick Tip to Solve: Place donor levels next to the conduction band and acceptor levels next to the valence band before judging band-energy statements.

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

Reason (R): Photoelectric current is proportional to frequency of incident radiation.

[1 mark]

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

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

Solution:

Concept:

- A photon carries energy $h\nu$, and transfers its energy to an electron in a single interaction; this explains the particle aspect of the photoelectric effect.
- Photoelectric current measures the number of electrons collected per second, whereas maximum electron kinetic energy is given by $K_m = h\nu - \phi$.

Step 1: Evaluate the assertion The threshold frequency and the dependence of maximum electron kinetic energy on frequency are explained by absorption of individual photons. The photoelectric effect therefore demonstrates the particle nature of light, so the assertion is true.

Step 2: Evaluate the reason Photoelectric current is not proportional to the frequency of incident radiation. For a fixed frequency above threshold and fixed collection conditions, increasing intensity increases the number of emitted electrons and hence the current. Changing frequency primarily changes the maximum kinetic energy. The reason is false.

Step 3: Test the explanatory link The proposed current-frequency proportionality is false, so it cannot explain the true assertion. Options (A) and (B) require a true reason, and option (D) requires a false assertion; these do not match this case.

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

Quick Tip to Solve: Separate the two effects: intensity controls photoelectron numbers at fixed frequency; frequency controls maximum kinetic energy.

15. Assertion (A): A proton and an electron enter a uniform magnetic field $\vec{B}$ with the same momentum $\vec{p}$ such that $\vec{p}$ is perpendicular to $\vec{B}$. They describe circular paths of the same radius.

Reason (R): In a magnetic field, orbital radius r is equal to $\frac{p}{qB}$.

[1 mark]

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

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

Solution:

Concept:

- For motion perpendicular to a uniform magnetic field, the magnetic force supplies centripetal force: $qvB = mv^2/r$, where q is the magnitude of charge.
- Since momentum magnitude is $p = mv$, the orbital radius is $r = p/(qB)$. A proton and an electron have equal charge magnitude e .

Step 1: Evaluate the assertion Both particles have the same momentum magnitude and enter the same magnetic field perpendicularly. Their radii are therefore $r_p = p/(eB)$ and $r_e = p/(eB)$, so the assertion is true. Their unequal masses imply unequal speeds, but do not change this equality of radii.

Step 2: Evaluate the reason Equating magnetic and centripetal forces and cancelling the speed gives $r = mv/(qB) = p/(qB)$. Thus the reason is true, with q understood as charge magnitude. The opposite signs of the charges reverse the directions of curvature, not the positive radii.

Step 3: Check the explanatory link The stated radius formula directly explains the assertion because both p and $q = e$ are equal for the two particles in the same B . Option (B) incorrectly denies this connection; options (C) and (D) incorrectly declare a true statement false.

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

Quick Tip to Solve: At equal momentum compare charge magnitudes in $r = p/(|q|B)$; the charge sign determines bending direction only.

16. Assertion (A): A convex lens, when immersed in a liquid, disappears.

Reason (R): The refractive indices of material of the lens and the liquid are equal.

[1 mark]

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

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

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

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

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

Solution:

Concept:

- Refraction at an interface depends on the ratio of refractive indices. For equal indices, Snell's law gives equal incidence and refraction angles.
- For a thin lens immersed in a medium, $1/f = (n_\ell/n_m - 1)(1/R_1 - 1/R_2)$, where n_ℓ and n_m are the lens and medium indices.

Step 1: Evaluate the assertion The assertion describes the observed disappearance of a transparent lens in the liquid under consideration. In the usual ideal optical model this occurs when its boundary produces no optical contrast. It does not mean that a convex lens disappears in every possible liquid.

Step 2: Evaluate the reason The reason supplies the condition for that observation: the lens material and liquid have equal refractive indices, $n_\ell = n_m$. Light then suffers no change of direction at either lens surface. The lens-maker expression also gives $1/f = 0$, so the immersed lens has zero power.

Step 3: Check the explanatory link With matched indices, the transparent lens cannot be distinguished optically from the surrounding liquid in this idealisation. Thus the reason is true for the stated disappearance and directly explains it. Option (B) overlooks this causal connection, while (C) and (D) deny the index-matching explanation.

Step 4: Conclusion For the index-matched liquid described, both statements are true and the reason explains the assertion. Hence, the correct option is (A).

Quick Tip to Solve: When an immersed transparent lens disappears, set its relative refractive index to unity; its optical power becomes zero.

Section B (10 marks)

17(a). What is meant by 'relaxation time' of free electrons in a conductor? Show that the resistance of a conductor can be expressed by $R = \frac{ml}{ne^2\tau A}$, where symbols have their usual meanings. [2 marks]

Solution:

Concept:

- Relaxation time τ is the mean time interval between two successive collisions of a conduction electron with the scattering centres in the conductor.
- Drift speed is $v_d = eE\tau/m$, and current magnitude is $I = neAv_d$. Here e is electron charge magnitude, m its mass, n the number of free electrons per unit volume, and A the cross-sectional

area.

Step 1: Relate drift speed to the applied potential difference Consider a uniform conductor of length l with potential difference V across its ends. Its electric field magnitude is $E = V/l$. Between collisions an electron accelerates under the electric force; averaging over the relaxation time gives the drift speed magnitude

$$v_d = \frac{eE\tau}{m} = \frac{eV\tau}{ml}.$$

Electron drift is opposite the electric field, whereas conventional current is along it; the equation here uses magnitudes.

Step 2: Obtain the current and resistance In unit time the electrons crossing any section carry charge $neAv_d$. Substituting the drift speed into the current expression gives

$$I = neA \frac{eV\tau}{ml} = \frac{ne^2 A \tau}{ml} V.$$

By Ohm's law, resistance is the ratio of the applied potential difference to the resulting current. Hence

$$R = \frac{V}{I} = \frac{ml}{ne^2 \tau A}.$$

Step 3: Conclusion Relaxation time is the average interval between successive electron collisions. The resistance is $R = ml/(ne^2 \tau A)$, with l the conductor length and all other symbols defined above.

Quick Tip to Solve: Start with $I = neAv_d$, substitute $v_d = eV\tau/(ml)$, and invert the coefficient of V to get resistance.

OR

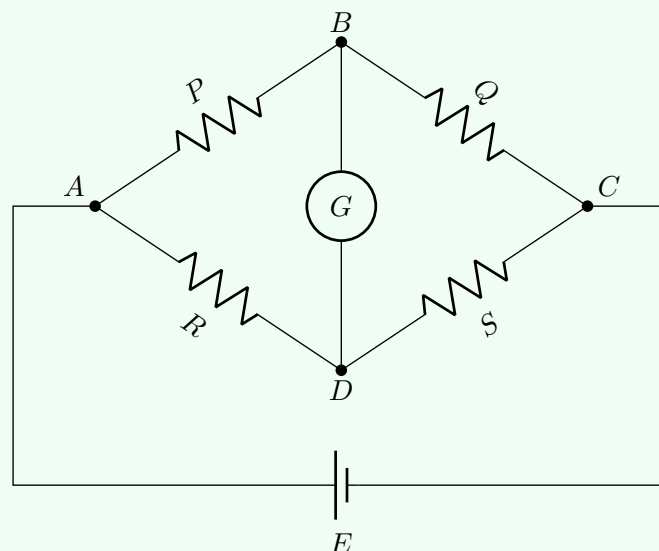
17(b). Draw the circuit diagram of a Wheatstone bridge. Obtain the condition when no current flows through the galvanometer in it. [2 marks]

Solution:

Concept:

- A Wheatstone bridge contains four resistances in a bridge arrangement, with a galvanometer across one diagonal and a cell across the other.
- At balance, galvanometer current is zero, so its end points have equal potential. Ohm's law then relates the potential drops along the two branches.

Step 1: Draw and label the bridge Connect resistances P, Q in the branch ABC , and R, S in the branch ADC . Place the galvanometer G between B and D , and the cell between A and C , as shown. Let the branch currents at balance be I_1 through P, Q and I_2 through R, S .



Wheatstone bridge: the cell is across AC, and the galvanometer is across BD.

Step 2: Apply the balance condition With no current through G , $V_B = V_D$, and each branch carries an unchanged current through its two resistances. Equal drops from A to B, D , and then from B, D to C , give respectively

$$I_1 P = I_2 R,$$

$$I_1 Q = I_2 S.$$

Dividing these equalities eliminates the branch currents:

$$\frac{P}{Q} = \frac{R}{S}.$$

Conversely, this resistance ratio makes the two junction potentials equal, so the galvanometer has no potential difference across it.

Step 3: Conclusion The galvanometer carries no current when the bridge is balanced: $\boxed{P/Q = R/S}$, or equivalently $PS = QR$.

Quick Tip to Solve: Mark the galvanometer junctions as equal-potential points, equate the drops on each side, and divide to remove the currents.

18. The magnifying power of an astronomical telescope is 24. In normal adjustment, distance between its two lenses is 150 cm. Find the focal length of the objective lens. [2 marks]

Solution:

Concept:

- For an astronomical telescope in normal adjustment, both object and final image are at infinity, and the lens separation is $L = f_o + f_e$.
- The magnitude of angular magnifying power is $|M| = f_o/f_e$, where f_o and f_e are the positive focal lengths of the objective and eyepiece.

Step 1: Express the focal lengths using magnifying power The stated magnifying power is its

magnitude, $|M| = 24$. Thus

$$\frac{f_o}{f_e} = 24, \quad f_o = 24f_e.$$

The objective must have the larger focal length. The signed magnification is negative because the final image is inverted, but this sign does not make either focal length negative.

Step 2: Use the lens separation in normal adjustment The objective forms the intermediate image at its second focal plane, which coincides with the first focal plane of the eyepiece. The separation is therefore the sum of the focal lengths, not their difference. Substituting the given distance gives

$$\begin{aligned} f_o + f_e &= 150 \text{ cm}, \\ 24f_e + f_e &= 150 \text{ cm}, \\ f_e &= 6 \text{ cm}, \\ f_o &= 24 \times 6 \text{ cm} = 144 \text{ cm}. \end{aligned}$$

The check $144 + 6 = 150$ confirms the separation, and $144/6 = 24$ confirms the magnifying power.

Step 3: Conclusion The focal length of the objective lens is $f_o = 144 \text{ cm} = 1.44 \text{ m}$.

Quick Tip to Solve: In normal adjustment use $f_o = L|M|/(|M| + 1)$; here this is $150 \times 24/25 \text{ cm}$.

19. Explain the following:

- (a) For a simple microscope, the angular size of the object equals the angular size of the image. Yet it offers magnification.
- (b) Both plane and convex mirrors produce virtual images of objects. Can they produce real images under some circumstances? [2 marks]

Solution:

Concept:

- Angular magnification is $M = \theta/\theta_0$, where θ is the angle seen through the microscope and θ_0 is the angle subtended by the unaided object at the least distance of distinct vision D .
- A real image forms wherever reflected rays actually converge. Incident converging rays provide a virtual object for a mirror.

Step 1: (a) Identify the correct reference angle With the eye close to a simple microscope, the object and its virtual image subtend approximately the same angle at the lens. However, this angle is compared with the angle subtended by the object when viewed comfortably without the lens at D , not with the angle of the nearby object at its actual position. The microscope allows the object to be placed at $|u| < D$, while its virtual image lies at a comfortable viewing distance. For an object of height h , the small-angle approximation gives

$$\theta \simeq \frac{h}{|u|}, \quad \theta_0 \simeq \frac{h}{D}, \quad M = \frac{D}{|u|} > 1.$$

Step 2: (b) Consider a converging incident beam Yes. For a plane mirror, rays directed towards a point behind the mirror converge after reflection to a real image at the corresponding point in front of it. A convex mirror can also form a real image if the incident rays converge sufficiently strongly: their would-be meeting point must lie between the pole and the focus behind the mirror. In the Cartesian

convention, $f > 0$ and this virtual object has $0 < u < f$. The mirror formula gives

$$\frac{1}{v} = \frac{1}{f} - \frac{1}{u} < 0,$$

so the reflected rays meet in front of the mirror, where $v < 0$.

Step 3: Conclusion (a) Magnification results from a larger angular size than unaided viewing at D . (b) Both mirrors can form real images when supplied with a suitable converging incident beam, that is, a virtual object.

Quick Tip to Solve: Always compare a microscope's angle with unaided viewing at the near point; for mirrors, first check whether the incident rays diverge or converge.

20. The minimum intensity of white light that our eyes can perceive is about 0.1 nW m^{-2} . Calculate the number of photons of this light entering our pupil (area 0.4 cm^2) per second. (Take average wavelength of white light = 500 nm and Planck's constant = $6.6 \times 10^{-34} \text{ J s}$) [2 marks]

Solution:

Concept:

- Intensity I is incident energy per unit area per unit time. The power entering a pupil of area A is $P = IA$.
- A photon of wavelength λ has energy $E = hc/\lambda$, where h is Planck's constant and $c = 3.0 \times 10^8 \text{ m s}^{-1}$. The photon arrival rate is $\dot{N} = P/E$.

Step 1: Convert the intensity and pupil area to SI units Since $1 \text{ nW} = 10^{-9} \text{ W}$ and $1 \text{ cm}^2 = 10^{-4} \text{ m}^2$,

$$\begin{aligned} I &= 0.1 \times 10^{-9} = 1.0 \times 10^{-10} \text{ W m}^{-2}, \\ A &= 0.4 \times 10^{-4} = 4.0 \times 10^{-5} \text{ m}^2, \\ P &= IA = 4.0 \times 10^{-15} \text{ J s}^{-1}. \end{aligned}$$

This power is the energy entering the pupil each second; the entire incident intensity must therefore be multiplied by the pupil area.

Step 2: Calculate the photon energy and arrival rate Approximate the photons of white light by the stated average wavelength, $\lambda = 500 \times 10^{-9} = 5.0 \times 10^{-7} \text{ m}$. Thus

$$\begin{aligned} E &= \frac{(6.6 \times 10^{-34})(3.0 \times 10^8)}{5.0 \times 10^{-7}} = 3.96 \times 10^{-19} \text{ J}, \\ \dot{N} &= \frac{4.0 \times 10^{-15}}{3.96 \times 10^{-19}} = 1.01 \times 10^4 \text{ s}^{-1}. \end{aligned}$$

Dividing joules per second by joules per photon gives photons per second, as required.

Step 3: Conclusion Approximately 1.0×10^4 photons enter the pupil per second.

Quick Tip to Solve: Use $\dot{N} = IA\lambda/(hc)$, and square the centimetre-to-metre conversion when converting the pupil area.

21. Suppose a pure Si crystal has 5×10^{28} atoms m^{-3} . It is doped by 1 ppm concentration of boron. Calculate the concentration of holes and electrons, given that $n_i = 1.5 \times 10^{16} \text{ m}^{-3}$. Is the doped crystal n -type or p -type? [2 marks]

Solution:

Concept:

- Trivalent boron is an acceptor impurity in tetravalent silicon. Each ionised acceptor contributes approximately one mobile hole.
- At thermal equilibrium, the mass-action law is $np = n_i^2$, where n , p and n_i denote electron, hole and intrinsic carrier concentrations, respectively.

Step 1: Find the acceptor and majority-carrier concentrations One part per million corresponds to an atomic fraction of 10^{-6} . The boron acceptor concentration is therefore

$$N_A = (5 \times 10^{28})(10^{-6}) = 5 \times 10^{22} \text{ m}^{-3}.$$

Boron has one fewer valence electron than silicon, creating a hole in bonding. Assuming complete ionisation and negligible donor impurities, charge neutrality gives $p = n + N_A$. Since $N_A \gg n_i$, the minority-electron concentration is negligible compared with N_A , and

$$p \simeq N_A = 5 \times 10^{22} \text{ m}^{-3}.$$

Step 2: Apply the mass-action law to the minority carriers Doping changes the individual electron and hole concentrations, but their equilibrium product remains n_i^2 at the specified temperature. Hence

$$n = \frac{n_i^2}{p} = \frac{(1.5 \times 10^{16})^2}{5 \times 10^{22}} = \frac{2.25 \times 10^{32}}{5 \times 10^{22}} = 4.5 \times 10^9 \text{ m}^{-3}.$$

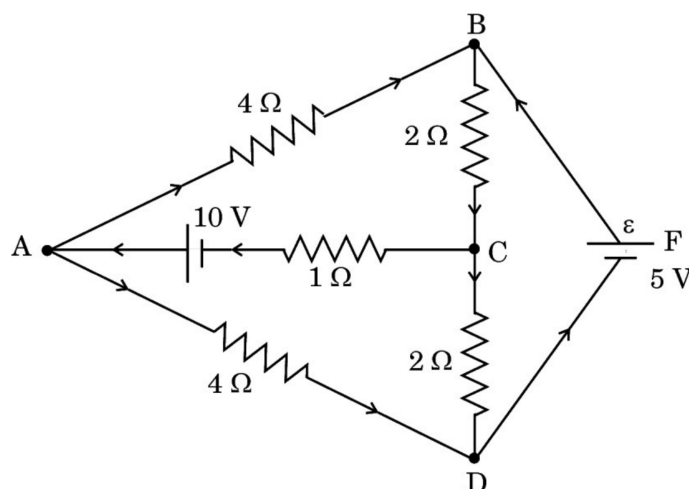
This value is indeed extremely small compared with the acceptor concentration, confirming the approximation used for p . Holes are the majority carriers because the dopant is an acceptor.

Step 3: Conclusion The hole concentration is $p \simeq 5 \times 10^{22} \text{ m}^{-3}$, the electron concentration is $n \simeq 4.5 \times 10^9 \text{ m}^{-3}$, and the crystal is p -type.

Quick Tip to Solve: Convert ppm to a fraction first; use the dopant concentration for the majority carriers and n_i^2 divided by it for the minority carriers.

Section C (21 marks)

22. Determine the current in branches AB , AC and BC of the network shown in figure. [3 marks]



Solution:

Concept:

- Kirchhoff's junction law states that the algebraic sum of currents leaving any node is zero. Through a resistor R , the current from node X to node Y is $(V_X - V_Y)/R$.
- An ideal cell raises potential from its negative to its positive terminal by its emf. The longer plate is positive: the 10 V cell is positive towards A , and the 5 V cell is positive towards B .

Step 1: Choose reference potentials and write the branch currents Set $V_C = 0$ and write $V_A = a$, $V_B = b$, with potentials in volts. The right-hand cell gives $V_D = b - 5$. Moving from A towards C , the 10 V cell lowers the potential by 10 V, so the current towards C through the $1\ \Omega$ resistor is $a - 10$. Thus, in amperes,

$$I_{AB} = \frac{a - b}{4}, \quad I_{AD} = \frac{a - b + 5}{4}, \quad I_{AC} = a - 10.$$

These are algebraic currents in the named directions; a negative result reverses the direction.

Step 2: Apply Kirchhoff's junction law At A , summing the three outgoing currents gives

$$\frac{a - b}{4} + \frac{a - b + 5}{4} + a - 10 = 0 \Rightarrow 6a - 2b = 35.$$

Treat B , D and their connecting ideal cell as a combined node group. The cell's internal branch current cancels when the two junction equations are added. Sum the currents from this group to A and C :

$$\frac{b - a}{4} + \frac{b}{2} + \frac{b - 5 - a}{4} + \frac{b - 5}{2} = 0 \Rightarrow 6b - 2a = 15.$$

Step 3: Solve for the potentials and determine directions The equations give $3a - b = 17.5$ and $3b - a = 7.5$. Substituting $b = 3a - 17.5$ into the second equation gives $8a = 60$, hence

$$V_A = 7.5\text{ V}, \quad V_B = 5.0\text{ V}, \quad V_D = V_C = 0.$$

Therefore,

$$\begin{aligned}I_{AB} &= \frac{7.5 - 5}{4} = 0.625 \text{ A}, \\I_{AC} &= \frac{7.5 - 10 - 0}{1} = -2.5 \text{ A}, \\I_{BC} &= \frac{5 - 0}{2} = 2.5 \text{ A}.\end{aligned}$$

The negative sign for I_{AC} means flow from C to A . As a check, $I_{AD} = 7.5/4 = 1.875 \text{ A}$; the outgoing currents at A add to $0.625 + 1.875 = 2.5 \text{ A}$, equal to the incoming current from C .

Step 4: Conclusion Branch AB : 0.625 A from A to B ; branch AC : 2.5 A from C to A ; branch BC : 2.5 A from B to C .

Quick Tip to Solve: Read each cell's longer plate before assigning signs; combining the two nodes across an ideal cell removes its unknown branch current.

23. Two long straight parallel conductors carrying currents, exert a force on each other. Why? Derive an expression for the force per unit length between two long straight parallel conductors carrying currents in opposite directions. Explain the nature of the force between these conductors. [3 marks]

Solution:

Concept:

- A long straight wire carrying current I produces a magnetic field $B = \mu_0 I / (2\pi r)$ at perpendicular distance r in air or vacuum; μ_0 is the permeability of free space.
- A straight conductor of length l , carrying current I in an external magnetic field, experiences $\vec{F} = I\vec{l} \times \vec{B}$. Its magnitude is $IlB \sin \theta$, where θ is the angle between current and field.

Step 1: Explain the interaction Each conductor produces a magnetic field in the region occupied by the other conductor. The moving charges constituting the current in the second conductor experience a magnetic force due to the first conductor's field, and conversely. Thus the force is a magnetic interaction between the two currents.

Step 2: Find the field and force on the second wire Let two very long parallel wires, separated by distance d , carry currents I_1 and I_2 in opposite directions. Neglect end effects. The first wire produces a field at the second wire of magnitude

$$B_1 = \frac{\mu_0 I_1}{2\pi d}.$$

This field is perpendicular to the second wire. Therefore the force on a length l of the second wire is

$$F_{21} = I_2 l B_1 \sin 90^\circ = \frac{\mu_0 I_1 I_2 l}{2\pi d}.$$

Interchanging the wires gives the same force magnitude on an equal length of the first wire.

Step 3: Determine the nature of the force Place wire 1 to the left of wire 2. If I_1 is upward, the right-hand thumb rule gives a field into the page at wire 2. Its current I_2 is downward, so $I_2 \vec{l} \times \vec{B}_1$ points to the right, away from wire 1. Similarly, the force on wire 1 points left, away from wire 2. Hence opposite currents repel, and the forces are equal in magnitude and opposite in direction.

Step 4: Conclusion For oppositely directed currents, the force per unit length is

$$\frac{F}{l} = \frac{\mu_0 I_1 I_2}{2\pi d} \quad \text{in N m}^{-1}.$$

The force is repulsive because each conductor is pushed away from the other.

Quick Tip to Solve: First find the field of one wire at the other; then use the other wire's current in $F = IlB$. Opposite currents repel.

24. A sinusoidal voltage is applied to an electric circuit containing a circuit element 'X' in which the current leads the voltage by $\frac{\pi}{2}$.

- (a) Identify the circuit element 'X' in the circuit.
- (b) Write the formula for its reactance.
- (c) Show graphically the variation of this reactance with frequency of ac voltage.
- (d) Explain the behaviour of this element when it is used in (i) an ac circuit, and (ii) a dc circuit.

[3 marks]

Solution:

Concept:

- For a capacitor of capacitance C , charge and voltage satisfy $q = Cv$, so its current is $i = dq/dt = C dv/dt$.
- Capacitive reactance is $X_C = 1/(\omega C) = 1/(2\pi fC)$, where f is frequency and $\omega = 2\pi f$ is angular frequency. Its SI unit is the ohm.

Step 1: Identify the element from its phase relation (a) The element X is an ideal capacitor. To see the phase relation, let the applied voltage be $v = V_m \sin \omega t$. Then

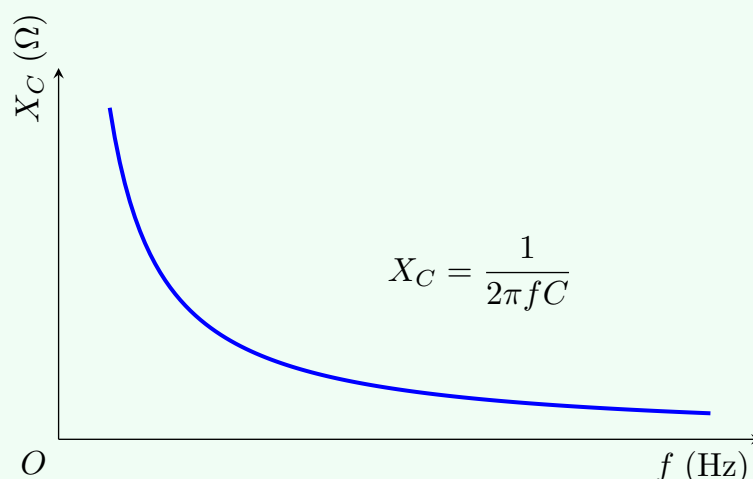
$$i = C \frac{dv}{dt} = \omega C V_m \cos \omega t = I_m \sin \left(\omega t + \frac{\pi}{2} \right).$$

Hence the current leads the voltage by $\pi/2$, exactly as specified. A resistor would have current in phase with voltage, while an inductor would have current lagging voltage.

Step 2: Write the reactance and plot its frequency dependence (b) The ratio of voltage amplitude to current amplitude gives

$$X_C = \frac{V_m}{I_m} = \frac{1}{\omega C} = \frac{1}{2\pi fC}.$$

(c) For a fixed capacitance, X_C is inversely proportional to f . Its graph is a decreasing rectangular hyperbola in the first quadrant. It tends to infinity as f tends to zero and tends to zero as frequency increases without bound; it does not meet either positive axis at a finite point.



Capacitive reactance versus frequency for fixed capacitance (schematic).

Step 3: Explain its behaviour with ac and dc (d)(i) With ac, the continuously changing voltage repeatedly charges and discharges the capacitor, so an alternating current exists in the external circuit. Its opposition is finite and equals X_C ; increasing frequency reduces that opposition. There is no conduction of charge through the ideal insulating dielectric, and an ideal capacitor consumes no average power over a complete cycle.

(ii) With dc, a transient charging current initially flows. Once the capacitor is fully charged, its voltage is constant, so $i = C dv/dt = 0$. It therefore blocks steady dc and behaves as an open circuit, consistent with $f = 0$ and $X_C \rightarrow \infty$.

Step 4: Conclusion The element is a capacitor with $X_C = 1/(2\pi fC)$. Its reactance decreases hyperbolically with frequency; it supports alternating current through charging and discharging but blocks steady direct current.

Quick Tip to Solve: Remember that differentiating a sine gives a cosine: $i = C dv/dt$ immediately proves the capacitor's current lead and its zero steady dc current.

25. The electric field in an electromagnetic wave in vacuum is given by:

$$\vec{E} = (6.3 \text{ N/C})[\cos((1.5 \text{ rad/m})y + (4.5 \times 10^8 \text{ rad/s})t)]\hat{i}$$

(a) Find the wavelength and frequency of the wave.

(b) What is the amplitude of the magnetic field of the wave?

(c) Write an expression for the magnetic field of this wave.

[3 marks]

Solution:

Concept:

- In a sinusoidal travelling wave, the wave number is $k = 2\pi/\lambda$ and angular frequency is $\omega = 2\pi f$, where λ is wavelength and f is frequency.
- For an electromagnetic wave in vacuum, $c = \omega/k = E_0/B_0$. Electric and magnetic fields are in phase, mutually perpendicular, and perpendicular to the propagation direction, which is along $\vec{E} \times \vec{B}$.

Step 1: Read the wave parameters and find wavelength and frequency (a) Compare the given cosine with $\cos(ky + \omega t)$. Its parameters are $k = 1.5 \text{ rad m}^{-1}$, $\omega = 4.5 \times 10^8 \text{ rad s}^{-1}$, and $E_0 = 6.3 \text{ N C}^{-1}$.

Thus

$$\lambda = \frac{2\pi}{k} = \frac{2\pi}{1.5} \text{ m} \simeq 4.19 \text{ m},$$
$$f = \frac{\omega}{2\pi} = \frac{4.5 \times 10^8}{2\pi} \text{ Hz} \simeq 7.16 \times 10^7 \text{ Hz}.$$

The phase speed $\omega/k = 3.0 \times 10^8 \text{ m s}^{-1}$ is consistent with propagation in vacuum.

Step 2: Calculate the magnetic-field amplitude (b) Use the vacuum relation $E_0 = cB_0$. Therefore

$$B_0 = \frac{E_0}{c} = \frac{6.3}{3.0 \times 10^8} \text{ T} = 2.1 \times 10^{-8} \text{ T}.$$

This is the peak amplitude, so no root-mean-square conversion is needed.

Step 3: Determine the direction and write the magnetic field (c) At fixed phase, $ky + \omega t = \text{constant}$, giving $dy/dt = -\omega/k$. The wave therefore travels in the negative y -direction. Since the electric field is along the x -axis, the magnetic field must be along the z -axis, with its sign chosen so that the energy flow is along $-\hat{j}$. Indeed,

$$\hat{i} \times \hat{k} = -\hat{j}.$$

The magnetic field has the same cosine phase as the electric field. Writing the phase separately keeps its units explicit:

$$\phi(y, t) = (1.5 \text{ rad m}^{-1})y + (4.5 \times 10^8 \text{ rad s}^{-1})t,$$
$$\vec{B}(y, t) = (2.1 \times 10^{-8} \text{ T}) \cos \phi(y, t) \hat{k}.$$

Both fields reverse together during the cycle, leaving $\vec{E} \times \vec{B}$ directed along negative y .

Step 4: Conclusion $\lambda \simeq 4.19 \text{ m}$, $f \simeq 7.16 \times 10^7 \text{ Hz}$, and $B_0 = 2.1 \times 10^{-8} \text{ T}$. The magnetic field is $(2.1 \times 10^{-8} \text{ T}) \cos \phi \hat{k}$, with the same phase ϕ as the given electric field and propagation along $-\hat{j}$.

Quick Tip to Solve: A phase $ky + \omega t$ travels toward negative y . Determine that direction first, then choose $\vec{B}$ using $\vec{E} \times \vec{B}$.

26. State Bohr's first and second postulates. Use them to derive an expression for the radius of the n th orbit in a hydrogen atom. [3 marks]

Solution:

Concept:

- Bohr's stationary orbits are permitted non-radiating electron orbits; their angular momentum is quantised as $m_e v_n r_n = n\hbar$, where $\hbar = h/(2\pi)$ and $n = 1, 2, 3, \dots$
- In hydrogen, the electrostatic attraction between the proton and electron provides the centripetal force. Here e is the magnitude of their charge, m_e is the electron mass, and ϵ_0 is the permittivity of free space.

Step 1: State the two postulates First postulate: an electron revolves around the nucleus only in certain stable circular orbits, called stationary orbits, without radiating electromagnetic energy. Its energy remains constant while it stays in one such orbit. Second postulate: only those circular orbits are allowed for which the electron's orbital angular momentum is an integral multiple of $h/(2\pi)$:

$$m_e v_n r_n = \frac{n\hbar}{2\pi}.$$

The positive integer n labels the orbit; the smallest allowed value is $n = 1$.

Step 2: Apply the radial force equation Treat the proton as fixed in the standard Bohr model. For an electron in the n th circular orbit, Coulomb attraction points towards the nucleus and supplies exactly the required centripetal force:

$$\frac{e^2}{4\pi\epsilon_0 r_n^2} = \frac{m_e v_n^2}{r_n}.$$

Thus $m_e v_n^2 r_n = e^2/(4\pi\epsilon_0)$. The electrostatic force is not an additional force to be added to the centripetal force; it is the source of it.

Step 3: Eliminate the orbital speed Angular-momentum quantisation gives $v_n = nh/(2\pi m_e r_n)$. Substituting this in the force equation,

$$\begin{aligned}\frac{e^2}{4\pi\epsilon_0 r_n^2} &= \frac{m_e}{r_n} \left(\frac{nh}{2\pi m_e r_n} \right)^2, \\ \frac{e^2 r_n}{4\pi\epsilon_0} &= \frac{n^2 h^2}{4\pi^2 m_e}.\end{aligned}$$

Solving this relation determines the discrete allowed radii rather than a continuous range of orbit sizes.

Step 4: Conclusion The radius of the n th hydrogen orbit is

$$r_n = \frac{\epsilon_0 h^2}{\pi m_e e^2} n^2 = a_0 n^2,$$

where $a_0 \simeq 5.29 \times 10^{-11}$ m is the Bohr radius. Hence the allowed radii grow as n^2 .

Quick Tip to Solve: Start with Coulomb force equal to centripetal force, then substitute the speed from $m_e v r = nh/(2\pi)$; the remaining radius must scale as n^2 .

27. (a) Define atomic mass unit (u).

(b) Calculate the energy required to separate a deuteron into its constituent parts (a proton and a neutron). Given:

$$m(D) = 2.014102 \text{ u}$$

$$m_H = 1.007825 \text{ u}$$

$$m_n = 1.008665 \text{ u}.$$

[3 marks]

Solution:

Concept:

- One atomic mass unit is defined as one-twelfth of the mass of a free, neutral carbon-12 atom at rest in its ground state: $1 \text{ u} = m(^{12}\text{C})/12$.
- Binding energy is the energy required to separate a nucleus completely into its free constituent nucleons. It is the mass defect multiplied by c^2 : $B = \Delta mc^2$, with $1 \text{ u } c^2 \simeq 931.5 \text{ MeV}$.

Step 1: Define the mass unit for part (a) The atomic mass unit (u) is exactly one-twelfth of the mass of a free, neutral carbon-12 atom at rest in its ground state. Numerically, $1 \text{ u} \simeq 1.6605 \times 10^{-27} \text{ kg}$. This definition fixes an atomic-scale mass standard and does not mean that every nucleon has a mass exactly equal to one u.

Step 2: Find the deuteron's mass defect for part (b) A deuteron contains one proton and one neutron. The given $m_H = 1.007825 \text{ u}$ is the mass of a neutral hydrogen atom, and the quoted $m(D) = 2.014102 \text{ u}$ is the corresponding deuterium atomic mass. Each atom contains one electron, so the electron masses cancel when these atomic masses are subtracted. Neglecting the tiny difference in atomic electronic binding energies, the nuclear mass defect is therefore

$$\begin{aligned}\Delta m &= m_H + m_n - m(D) \\ &= (1.007825 + 1.008665 - 2.014102) \text{ u} \\ &= 0.002388 \text{ u}.\end{aligned}$$

The separated constituents have the greater total mass, so energy must be supplied to dissociate the bound deuteron.

Step 3: Convert the mass defect to separation energy Applying mass-energy equivalence,

$$\begin{aligned}B &= 0.002388 \times 931.5 \text{ MeV} \\ &= 2.224422 \text{ MeV}.\end{aligned}$$

This is the energy for the entire deuteron; it is not the binding energy per nucleon. Using $1 \text{ MeV} = 1.602 \times 10^{-13} \text{ J}$, it is approximately $3.56 \times 10^{-13} \text{ J}$.

Step 4: Conclusion (a) $1 \text{ u} = m(^{12}\text{C})/12$, for a free neutral ground-state atom at rest. (b) The energy required to separate the deuteron into a proton and a neutron is $B \simeq 2.224 \text{ MeV}$, or $3.56 \times 10^{-13} \text{ J}$.

Quick Tip to Solve: When the data give hydrogen and deuterium atomic masses, use $m_H + m_n - m(D)$: one electron mass cancels on each side, so do not subtract it again.

28(a). Draw the circuit diagrams for obtaining the $V - I$ characteristics of a $p-n$ junction diode. Explain briefly the salient features of the $V - I$ characteristics in (i) forward biasing, and (ii) reverse biasing. [3 marks]

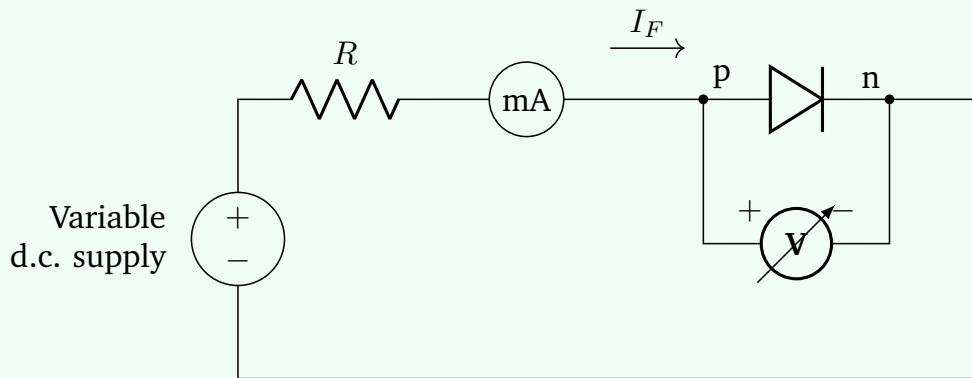
Solution:

Concept:

- Forward bias connects the p-side to the positive terminal and the n-side to the negative terminal, reducing the junction barrier and depletion width; reverse bias interchanges the supply polarity and increases them.
- A diode characteristic records current I against the voltage V across the junction. Connect the current meter in series and the voltmeter in parallel with the diode; a series resistance limits current.

Step 1: Set up the forward-bias circuit Use the circuit below with the positive terminal of the variable d.c. supply connected towards the diode's p-side. The milliammeter measures the forward current, and the voltmeter measures the junction voltage. Increase the applied voltage gradually and record corresponding readings (V_F, I_F). A series resistor R protects the diode. The supply and meter

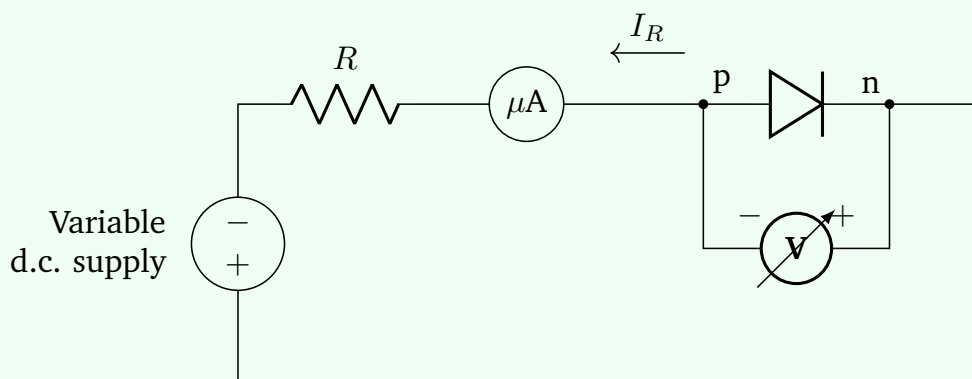
polarities must agree with the indicated forward current; the voltmeter's positive terminal is towards p.



Forward-bias measurement circuit; conventional current passes from p to n.

Step 2: Explain the forward characteristic At small forward voltage the current is very small because the junction potential barrier still opposes the flow of majority carriers. As forward voltage rises, the barrier height and depletion width decrease. Beyond the knee (cut-in) voltage, a small additional increase in voltage causes a large increase in current. The curve is nonlinear and the diode has a low incremental resistance in this conducting region. Typical knee voltages are about 0.7 V for silicon and 0.3 V for germanium; the turn-on is gradual, not an abrupt ideal switch.

Step 3: Reverse the supply and measure the reverse current In the second circuit the negative terminal is towards p and the positive terminal towards n. Replace the milliammeter with a microammeter because the reverse current before breakdown is very small. Connect the voltmeter's positive terminal towards n and the microammeter's positive terminal towards the n-side current path. Vary the reverse voltage in small steps and note (V_R , I_R), keeping the current limited by R .



Reverse-bias measurement circuit; the small reverse current passes from n to p.

Step 4: Explain the reverse characteristic Reverse bias increases the barrier and widens the depletion layer, suppressing majority-carrier current. A small current due to minority carriers flows in the opposite direction to forward current. At a fixed temperature this reverse saturation current is nearly independent of reverse voltage until breakdown. At the breakdown voltage its magnitude increases sharply; an ordinary diode can be damaged unless the current is limited. With forward voltage and

current taken positive, the forward branch lies in the first quadrant and the reverse branch in the third quadrant of the signed V - I plot.

Step 5: Conclusion The required circuits use a series milliammeter for forward bias and a series microammeter for reverse bias, with a voltmeter across the diode in both cases. Forward current rises rapidly beyond the knee; reverse current remains small and nearly constant until it rises sharply at breakdown.

Quick Tip to Solve: Check p-to-positive for forward bias and p-to-negative for reverse bias. Use mA for the forward branch and microamperes for the small reverse current.

OR

28(b). On the basis of energy band diagrams, distinguish between (i) an insulator, (ii) a semiconductor, and (iii) a conductor. [3 marks]

Solution:

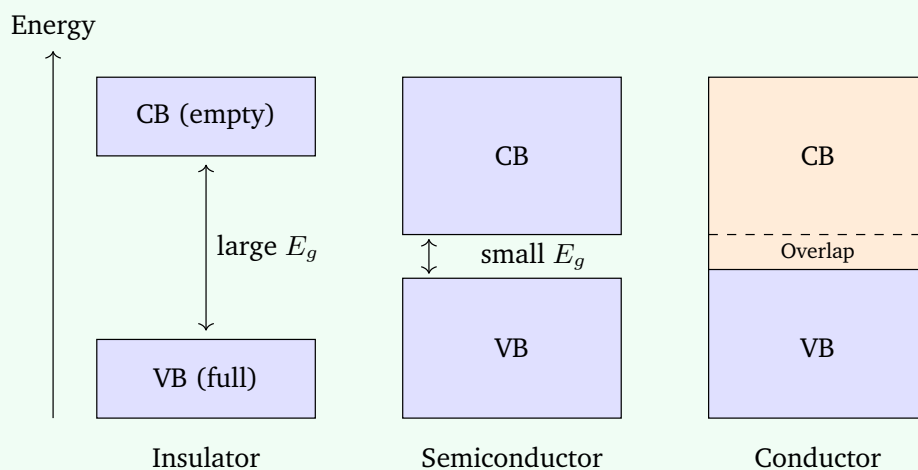
Concept:

- The valence band (VB) contains the outer electrons involved in bonding; the conduction band (CB) provides electronic states in which electrons can move through the solid.
- The forbidden energy gap $E_g = E_C - E_V$ separates the top of the valence band and the bottom of the conduction band. Its size and the occupation of the bands determine electrical conduction.

Step 1: Explain the insulator In an insulator the valence band is full and the conduction band is empty at low temperature. A large forbidden energy gap, typically several electron volts, separates them. Ordinary thermal energy at room temperature cannot excite an appreciable number of electrons across this gap. A filled band alone cannot provide normal conduction because nearby accessible empty states are absent, so the electrical conductivity is extremely small.

Step 2: Explain the semiconductor In an intrinsic semiconductor the valence band is full and the conduction band is empty at 0 K, but the forbidden gap is small, of order 1 eV. At room temperature some electrons gain enough thermal energy to enter the conduction band, leaving holes in the valence band. Both conduction electrons and holes carry current. Consequently conductivity is moderate and rises as temperature supplies more charge carriers.

Step 3: Explain the conductor A conductor has a partially filled allowed band, or overlapping valence and conduction bands. Thus no forbidden energy gap prevents electrons from reaching nearby vacant states. Even a small applied electric field changes the motion of many mobile electrons, producing a large current. The overlapping-band diagram below represents the usual metallic conductor model; a partially filled band gives the same conducting behaviour.



Schematic energy bands; the conductor shows overlapping bands. Energy increases upward.

Step 4: Conclusion An insulator has a large forbidden gap, a semiconductor has a small forbidden gap, and a conductor has overlapping bands or a partially filled band. These band structures explain their very low, intermediate and high conductivities respectively.

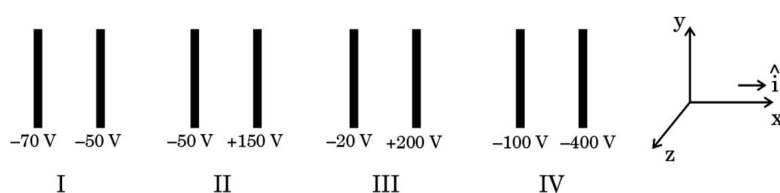
Quick Tip to Solve: Compare the gap and the availability of empty states: large gap means insulation, small gap permits thermal carriers, and overlap permits easy conduction.

Section D (8 marks)

Case Study Based Questions

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

29. The figure shows four pairs of parallel identical conducting plates, separated by the same distance 2.0 cm and arranged perpendicular to x-axis. The electric potential of each plate is mentioned. The electric field between a pair of plates is uniform and normal to the plates. [4 marks]



29(i). For which pair of the plates is the electric field $\vec{E}$ along $\hat{i}$? [1 mark]

- (A) I
- (B) II
- (C) III
- (D) IV

Correct Answer: (D) IV

Solution:

Concept:

- Along the horizontal axis, $E_x = -dV/dx$: electric field points from higher to lower potential.

- For plates separated by d , a uniform field has $E_x = (V_L - V_R)/d$, where V_L and V_R are the left and right plate potentials.

Step 1: Compare the plate potentials A field along $+\hat{i}$ requires the potential to decrease from left to right. In pairs I, II and III the potential increases: -70 to -50 V, -50 to $+150$ V, and -20 to $+200$ V, respectively. Their fields therefore point along $-\hat{i}$, ruling out (A), (B) and (C).

Step 2: Check pair IV Here the potential falls from -100 V on the left to -400 V on the right. Notice that -100 V is the higher potential even though both values are negative. With $d = 0.020$ m,

$$E_x = \frac{-100 - (-400)}{0.020} = +1.5 \times 10^4 \text{ V m}^{-1}.$$

Step 3: Conclusion The electric field in pair IV is along $+\hat{i}$. Hence, the correct option is (D).

Quick Tip to Solve: Read signed potentials from left to right: only a decrease in potential gives a field along the positive x-axis.

29(ii). An electron is released midway between the plates of pair IV. It will:

[1 mark]

- (A) move along $\hat{i}$ at constant speed
- (B) move along $-\hat{i}$ at constant speed
- (C) accelerate along $\hat{i}$
- (D) accelerate along $-\hat{i}$

Correct Answer: (D) accelerate along $-\hat{i}$

Solution:

Concept:

- The electric field points from higher to lower potential, with $E_x = (V_L - V_R)/d$ for parallel plates separated by d .
- An electron has charge $-e$, so its force $\vec{F} = -e\vec{E}$ and acceleration $\vec{a} = \vec{F}/m$ are opposite to the electric field.

Step 1: Determine the field direction Pair IV has left and right potentials -100 V and -400 V. Potential decreases towards the right, so $\vec{E}$ is along $+\hat{i}$. The field is nonzero and uniform throughout the gap, including its midpoint.

Step 2: Apply the electron's negative charge Since the electron carries negative charge, its force and acceleration point to the left, along $-\hat{i}$. Released means it starts from rest; it then gains speed towards the higher-potential left plate. Constant speed in (A) and (B) is impossible under this nonzero force, while (C) incorrectly takes electron acceleration in the field direction.

Step 3: Conclusion The electron accelerates along $-\hat{i}$. Hence, the correct option is (D).

Quick Tip to Solve: First find the field from the potentials; reverse its direction once for an electron's force and acceleration.

29(iii). Let V_0 be the potential at the left plate of any set, taken to be at $x = 0$ m. Then potential V at any point ($0 \leq x \leq 2$ cm) between the plates of that set can be expressed as: (α is a constant, positive or negative.) [1 mark]

- (A) $V = V_0 + \alpha x$
(B) $V = V_0 + \alpha x^2$
(C) $V = V_0 + \alpha x^{1/2}$
(D) $V = V_0 + \alpha x^{3/2}$

Correct Answer: (A) $V = V_0 + \alpha x$

Solution:

Concept:

- The potential gradient and electric field obey $E_x = -dV/dx$.
- A uniform electric field has constant E_x ; therefore its potential changes linearly with position, with the slope measured in V m^{-1} .

Step 1: Integrate the uniform field relation Use the left plate as the origin and impose $V(0) = V_0$. Integrating a constant field gives

$$V(x) - V_0 = - \int_0^x E_x dx' = -E_x x.$$

Thus the coefficient of x is constant, and its sign depends on which plate has the higher potential.

Step 2: Compare the proposed powers Set $\alpha = -E_x$, so the required potential is $V_0 + \alpha x$. Differentiating the other options gives field magnitudes proportional to x , $x^{-1/2}$, and $x^{1/2}$, respectively. Each varies with position for the nonzero potential differences shown, contradicting the stated uniform field.

Step 3: Conclusion $V = V_0 + \alpha x$, where $\alpha = -E_x$ is constant. Hence, the correct option is (A).

Quick Tip to Solve: Differentiate each proposed potential once: a uniform field requires a constant slope, so choose the linear expression.

29(iv)(a). Let E_1 , E_2 , E_3 and E_4 be the magnitudes of the electric field between the pairs of plates, I, II, III and IV respectively. Then: [1 mark]

- (A) $E_1 > E_2 > E_3 > E_4$
(B) $E_3 > E_4 > E_1 > E_2$
(C) $E_4 > E_3 > E_2 > E_1$
(D) $E_2 > E_3 > E_4 > E_1$

Correct Answer: (C) $E_4 > E_3 > E_2 > E_1$

Solution:

Concept:

- The magnitude of the uniform electric field between plates is $E = |V_R - V_L|/d$, where d is the plate separation.
- Since all four pairs have the same separation $d = 2.0 \text{ cm} = 0.020 \text{ m}$, their field magnitudes have the same ordering as the absolute potential differences.

Step 1: Find the four potential differences Subtract signed plate potentials before taking the absolute value:

$$|\Delta V_1| = |-50 - (-70)| = 20 \text{ V},$$

$$|\Delta V_2| = |150 - (-50)| = 200 \text{ V},$$

$$|\Delta V_3| = |200 - (-20)| = 220 \text{ V},$$

$$|\Delta V_4| = |-400 - (-100)| = 300 \text{ V}.$$

Step 2: Rank the field magnitudes Dividing by 0.020 m gives $E_1 = 1000$, $E_2 = 10000$, $E_3 = 11000$, and $E_4 = 15000$, all in V m^{-1} . Pair IV has the greatest field magnitude because its voltage difference is largest, followed by pairs III, II and I. Option (A) reverses this order, while (B) and (D) incorrectly put another pair ahead of IV.

Step 3: Conclusion $E_4 > E_3 > E_2 > E_1$. Hence, the correct option is (C).

Quick Tip to Solve: For equal plate spacing, rank the absolute voltage differences directly; negative potentials do not imply a negative field magnitude.

OR

29(iv)(b). An electron is projected from the right plate of set I directly towards its left plate. It just comes to rest at the plate. The speed with which it was projected is about: (Take $e/m = 1.76 \times 10^{11} \text{ C/kg}$) [1 mark]

(A) $1.3 \times 10^5 \text{ m/s}$

(B) $2.6 \times 10^6 \text{ m/s}$

(C) $6.5 \times 10^5 \text{ m/s}$

(D) $5.2 \times 10^7 \text{ m/s}$

Correct Answer: (B) $2.6 \times 10^6 \text{ m/s}$

Solution:

Concept:

- Electrostatic energy is conserved: $K_i + qV_i = K_f + qV_f$, where K is kinetic energy and q is charge.
- For an electron $q = -e$; moving towards lower potential raises its potential energy and reduces its kinetic energy.

Step 1: Find the kinetic energy lost The electron starts at $V_i = -50 \text{ V}$ and stops at $V_f = -70 \text{ V}$. Its potential energy increases by

$$\Delta U = (-e)\{(-70) - (-50)\} = 20e \text{ V}.$$

With zero final kinetic energy, conservation of energy gives $\frac{1}{2}mv^2 = e(20 \text{ V})$. The force opposes its initial leftward motion, so it slows down.

Step 2: Calculate the projection speed Substitute the given charge-to-mass ratio:

$$\begin{aligned} v &= \sqrt{2(e/m)(20 \text{ V})} = \sqrt{2(1.76 \times 10^{11})(20)} \text{ m s}^{-1} \\ &\simeq 2.65 \times 10^6 \text{ m s}^{-1}. \end{aligned}$$

This agrees approximately with (B). Options (A) and (C) provide too little kinetic energy; (D) provides

too much for the electron to stop at the left plate.

Step 3: Conclusion The speed is about $2.6 \times 10^6 \text{ m s}^{-1}$. Hence, the correct option is (B).

Quick Tip to Solve: For an electron just stopped by a retarding voltage, use $v = \sqrt{2(e/m)|\Delta V|}$; the plate separation cancels.

30. Diffraction and interference are closely related phenomena that occur together. Diffraction is the phenomenon of bending of light around the edges of the obstacle, while interference is the combination of waves that results in a new wave pattern. In order to get interference, there must be at least two waves that are diffracting. So while diffraction can occur without interference, interference cannot occur without diffraction.

Two slits of width $2 \mu\text{m}$ each in an opaque material are separated by a distance of $6 \mu\text{m}$. Monochromatic light of wavelength 450 nm is incident normally on the slits. One finds a combined interference and diffraction pattern on the screen. [4 marks]

30(i). The number of peaks of the interference fringes formed within the central peak of the envelope of the diffraction pattern will be: [1 mark]

- (A) 2
- (B) 3
- (C) 4
- (D) 6

Correct Answer: No printed option is exactly correct: five nonvanishing nominal interference orders lie within the central envelope. Option (D) gives the likely intended width-ratio estimate, six.

Solution:

Concept:

- For slit width a , wavelength λ and screen distance D , the central diffraction envelope has width $W = 2D\lambda/a$.
- For slit separation d , the interference fringe spacing is $\beta = D\lambda/d$. The usual fringe-width estimate within the envelope is $W/\beta = 2d/a$.

Step 1: Compare the envelope width with fringe spacing Insert $a = 2 \mu\text{m}$ and $d = 6 \mu\text{m}$. The wavelength and screen distance cancel, giving

$$\frac{W}{\beta} = \frac{2d}{a} = \frac{2 \times 6}{2} = 6.$$

Thus the central envelope spans six fringe spacings. Option (B), three, uses the half-width of the envelope; options (A) and (C) do not give the full-width ratio.

Step 2: Distinguish the examination estimate from missing orders The options appear to use the standard width-ratio estimate. Strictly, nominal bright orders satisfy $d \sin \theta = m\lambda$, and being inside the envelope requires $|m| < d/a = 3$. Hence only $m = 0, \pm 1, \pm 2$ are nonvanishing interference orders: the orders $m = \pm 3$ coincide with diffraction minima. Their exact count is five, which is absent from the printed options. Six is therefore the likely intended fringe-width answer, rather than a literal count of those orders.

Step 3: Conclusion There are 5 nonvanishing nominal interference orders, which is not among the

printed options. Option (D), 6, is the likely intended envelope-width estimate; it is not an exact order count. Therefore no listed option is exactly correct as worded.

Quick Tip to Solve: Use $2d/a$ for the envelope-to-fringe width ratio, but check missing boundary orders before interpreting this ratio as an exact peak count.

30(ii). The number of peaks of the interference formed if the slit width is doubled while keeping the distance between the slits same will be: [1 mark]

- (A) 1
- (B) 2
- (C) 3
- (D) 4

Correct Answer: (C) 3

Solution:

Concept:

- The central diffraction envelope width is $W = 2D\lambda/a$, where a is the slit width, D is the screen distance and λ is the wavelength.
- The interference spacing is $\beta = D\lambda/d$, with d the slit separation. Doubling a halves the envelope width while leaving β unchanged.

Step 1: Use the doubled slit width The new width is $a' = 2a = 4\ \mu\text{m}$, while $d = 6\ \mu\text{m}$ stays fixed. The number obtained by comparing the central envelope with the interference spacing is

$$N = \frac{2d}{a'} = \frac{2 \times 6}{4} = 3.$$

Thus the ratio falls by a factor of two from its original value.

Step 2: Check the allowed bright orders Bright interference orders within the central envelope obey $|m| < d/a' = 1.5$. The allowed integers are $m = -1, 0, +1$, so three nominal bright orders occur, agreeing with the width-ratio estimate here. Option (A) counts only the central order, option (B) omits the central order, and option (D) does not satisfy the allowed-order condition.

Step 3: Conclusion There are 3 interference fringes within the central diffraction envelope. Hence, the correct option is (C).

Quick Tip to Solve: When only slit width doubles, halve the diffraction envelope width; the fringe spacing is unchanged because the slit separation remains fixed.

30(iii)(a). If instead of 450 nm light, another light of wavelength 680 nm is used, number of peaks of the interference formed in the central peak of the envelope of the diffraction pattern will be: [1 mark]

- (A) 2
- (B) 4
- (C) 6
- (D) 9

Correct Answer: No printed option is exactly correct: five nonvanishing nominal interference orders lie within the central envelope. Option (C) gives the likely intended width-ratio estimate, six.

Solution:

Concept:

- The width of the central diffraction envelope is $W = 2D\lambda/a$, and the interference spacing is $\beta = D\lambda/d$, where a is slit width and d is slit separation.
- Their ratio $W/\beta = 2d/a$ is independent of wavelength. Changing wavelength scales both widths by the same factor.

Step 1: Cancel the wavelength in the ratio Replacing 450 nm by 680 nm increases both the diffraction envelope width and interference spacing by 680/450. Using the original slit dimensions,

$$\frac{W'}{\beta'} = \frac{2D\lambda'/a}{D\lambda'/d} = \frac{2d}{a} = \frac{2 \times 6}{2} = 6.$$

The option nine incorrectly increases the count with wavelength. Two and four do not equal the envelope-to-spacing ratio.

Step 2: Check the interpretation of the peak count The width-ratio convention in the options therefore predicts the same answer as before. For a literal count of nonvanishing nominal bright orders, however, $|m| < d/a = 3$, so $m = 0, \pm 1, \pm 2$ give five orders; $m = \pm 3$ are missing at the diffraction minima. This exact-order count also stays independent of wavelength and is absent from the options. The printed alternatives appear to use the conventional width estimate of six.

Step 3: Conclusion There are 5 nonvanishing nominal interference orders, which is not among the printed options. Option (C), 6, is the likely intended envelope-width estimate; it is not an exact order count. Therefore no listed option is exactly correct as worded.

Quick Tip to Solve: When only the wavelength changes, both the envelope width and fringe spacing change together; their ratio and the allowed-order condition stay unchanged.

30(iii)(b). Consider the diffraction of light by a single slit described in this case study. The first minimum falls at an angle θ equal to: [1 mark]

- (A) $\sin^{-1}(0.12)$
- (B) $\sin^{-1}(0.225)$
- (C) $\sin^{-1}(0.32)$
- (D) $\sin^{-1}(0.45)$

Correct Answer: (B) $\sin^{-1}(0.225)$

Solution:

Concept:

- Single-slit diffraction minima occur at $a \sin \theta = n\lambda$, where a is slit width, λ is wavelength and $n = 1, 2, \dots$
- The first minimum has $n = 1$. Use the width of one slit, not the separation between the two slits.

Step 1: Convert the printed quantities to common units This alternative refers to the original case-study light: $\lambda = 450 \text{ nm}$, not the changed wavelength in the other alternative. The slit width is $a = 2 \mu\text{m} = 2000 \text{ nm}$. Thus both quantities may be divided directly in nanometres.

Step 2: Apply the first-minimum condition Put $n = 1$ in the diffraction condition:

$$\sin \theta = \frac{\lambda}{a} = \frac{450}{2000} = 0.225.$$

Taking the inverse sine yields the angle on either side of the central axis in magnitude. The arguments 0.12, 0.32 and 0.45 in the other options do not equal the wavelength-to-width ratio; 0.45 would instead describe the second minimum.

Step 3: Conclusion The first minimum occurs at $\theta = \sin^{-1}(0.225)$. Hence, the correct option is (B).

Quick Tip to Solve: For a first diffraction minimum, calculate wavelength divided by slit width after expressing both lengths in the same unit.

30(iv). The number of bright fringes formed due to interference on 1 m of screen placed at $\frac{4}{3} \text{ m}$ away from the slits is: [1 mark]

- (A) 2
- (B) 3
- (C) 6
- (D) 10

Correct Answer: (D) 10

Solution:

Concept:

- In Young's double-slit approximation, the bright-fringe spacing is $\beta = \lambda D/d$, where λ is wavelength, D is screen distance and d is slit separation.
- The conventional number of interference fringes across a screen length L is $N = L/\beta$. This counts

fringe widths along the screen.

Step 1: Calculate the fringe spacing Use the distance printed in the official paper, $D = 4/3$ m, with $\lambda = 450 \times 10^{-9}$ m and $d = 6 \times 10^{-6}$ m. Then

$$\beta = \frac{(450 \times 10^{-9})(4/3)}{6 \times 10^{-6}} = 0.10 \text{ m.}$$

The slit separation determines this spacing; the individual slit width instead determines the diffraction envelope.

Step 2: Divide the screen length by the spacing For the stated screen length $L = 1$ m,

$$N = \frac{L}{\beta} = \frac{1}{0.10} = 10.$$

Thus ten interference fringe widths fit in the given length, as intended by the options. Two, three and six do not follow from the calculated spacing. This standard estimate does not count a pair of boundary maxima separately or subtract orders suppressed by the diffraction envelope; the question asks for the interference fringe count over a screen length.

Step 3: Conclusion The conventional interference-fringe count is 10. Hence, the correct option is (D).

Quick Tip to Solve: Read the printed distance as $4/3$ m, calculate β , and divide the specified screen length by that spacing.

Section E (15 marks)

31(a). (i) Obtain the expression for the capacitance of a parallel plate capacitor with a dielectric medium between its plates.

(ii) A charge of $6 \mu\text{C}$ is given to a hollow metallic sphere of radius 0.2 m. Find the potential at (i) the surface and (ii) the centre of the sphere. [5 marks]

Solution:

Concept:

- Capacitance is $C = Q/V$, where Q is the magnitude of charge on either plate and V is the potential difference between the plates.
- For a uniform dielectric of relative permittivity K , the permittivity is $\epsilon = K\epsilon_0$. Polarisation reduces the field for a given free plate charge.
- An isolated conducting sphere has surface potential $V = kQ/R$, taking potential at infinity as zero. Electrostatic equilibrium makes the entire conductor and its empty cavity equipotential.

Step 1: (i) Specify the parallel-plate arrangement Consider two large parallel conducting plates, each of area A , separated by a distance d . Give them charges $+Q$ and $-Q$, so the magnitude of free surface charge density is $\sigma = Q/A$. A uniform dielectric of relative permittivity K completely fills the gap. Assume d is small compared with the plate dimensions, so edge effects can be neglected and the electric field between the plates is uniform.

Step 2: (i) Find the field and potential difference In vacuum the fields of the two oppositely charged plates add between them, giving $E_0 = \sigma/\epsilon_0$. The dielectric develops bound charges whose field

opposes the original field. The resulting field is

$$E = \frac{E_0}{K} = \frac{\sigma}{K\epsilon_0} = \frac{Q}{K\epsilon_0 A}.$$

Since the field is uniform, the magnitude of the potential difference is

$$V = Ed = \frac{Qd}{K\epsilon_0 A}.$$

Step 3: (i) Obtain the capacitance Substitute this potential difference in the definition of capacitance:

$$C = \frac{Q}{V} = \frac{Q}{Qd/(K\epsilon_0 A)} = \frac{K\epsilon_0 A}{d}.$$

Thus a dielectric filling the entire gap increases the capacitance by a factor K compared with the vacuum value $C_0 = \epsilon_0 A/d$. This expression depends on the plate geometry and the medium, not on the particular charge used in its derivation.

Step 4: (ii) Calculate the potential at the surface For the metallic sphere, $Q = 6 \times 10^{-6} \text{ C}$ and $R = 0.2 \text{ m}$. Outside a spherically symmetric charged conductor, the potential is the same as that of a point charge at its centre. Hence, using $k = 9 \times 10^9 \text{ N m}^2 \text{ C}^{-2}$,

$$V_{\text{surface}} = \frac{kQ}{R} = \frac{(9 \times 10^9)(6 \times 10^{-6})}{0.2} = 2.7 \times 10^5 \text{ V}.$$

Step 5: (ii) Relate the centre potential to the surface potential The excess charge resides on the outer surface. There is no electric field anywhere inside the empty hollow sphere, so there is no potential difference between the centre and the surface:

$$V_{\text{centre}} - V_{\text{surface}} = - \int_{\text{surface}}^{\text{centre}} \vec{E} \cdot d\vec{l} = 0.$$

A zero field means constant potential, not zero potential. The common potential remains positive because the sphere carries a positive charge relative to infinity.

Step 6: Conclusion (i) The dielectric-filled parallel-plate capacitor has $C = K\epsilon_0 A/d$. (ii) The potentials at both the surface and the centre are $+2.7 \times 10^5 \text{ V}$, with zero potential chosen at infinity.

Quick Tip to Solve: For a completely filled capacitor multiply the vacuum capacitance by K . For a hollow charged conductor use the surface radius to find its potential everywhere inside; do not insert $r = 0$ into the exterior formula.

31(b). (i) A charge $+Q$ is placed on a thin conducting spherical shell of radius R . Use Gauss's theorem to derive an expression for the electric field at a point lying (i) inside and (ii) outside the shell.

(ii) Show that the electric field for same charge density (σ) is twice in case of a conducting plate or surface than in a nonconducting sheet. [5 marks]

Solution:

Concept:

- Gauss's theorem states $\oint \vec{E} \cdot d\vec{A} = Q_{\text{enc}}/\epsilon_0$, where Q_{enc} is the net charge enclosed by a closed Gaussian surface.
- Spherical symmetry makes the field radial and constant in magnitude on a concentric spherical Gaussian surface. The field inside a conductor in electrostatic equilibrium is zero.
- At a conducting surface the normal field just outside is $E = \sigma/\epsilon_0$, where σ is the local surface charge per unit area. An infinite uniformly charged nonconducting sheet produces equal outward fields on its two sides.

Step 1: (i) Choose a spherical Gaussian surface An isolated thin conducting spherical shell of radius R carries charge $+Q$. In electrostatic equilibrium, the charge is uniformly distributed over its outer surface because of spherical symmetry. Choose a concentric spherical Gaussian surface of radius r . Symmetry makes $\vec{E}$ radial and its magnitude the same at every point of this surface. Thus its total flux is $E(r)4\pi r^2$.

Step 2: (i) Apply Gauss's theorem inside the shell For $r < R$, all the shell's charge lies outside the Gaussian surface. It therefore encloses zero charge:

$$E(r)4\pi r^2 = \frac{0}{\epsilon_0}, \quad E(r) = 0 \quad (r < R).$$

This vanishing field follows from both Gauss's theorem and spherical symmetry; zero enclosed charge alone would not imply zero field in an arbitrary nonsymmetric arrangement. The centre also has zero field by symmetry.

Step 3: (i) Apply Gauss's theorem outside the shell For $r > R$, the Gaussian surface encloses the whole charge $+Q$. Therefore,

$$E(r)4\pi r^2 = \frac{Q}{\epsilon_0}, \quad \vec{E}(r) = \frac{Q}{4\pi\epsilon_0 r^2} \hat{r}.$$

Here $\hat{r}$ points radially outward. Thus the external field is the same as that of a point charge $+Q$ placed at the centre. Just outside the shell its magnitude is $Q/(4\pi\epsilon_0 R^2)$, while the limiting field just inside is zero.

Step 4: (ii) Find the field immediately outside a conducting surface Consider a small cylindrical Gaussian pillbox crossing the conducting surface, with flat faces of area a parallel to it. One face lies just outside and the other inside the conductor. The interior field vanishes, the exterior field is normal to the surface, and the curved side contributes no flux in the thin-pillbox limit. If the charge density on this surface is σ , Gauss's theorem gives

$$E_{\text{cond}}a = \frac{\sigma a}{\epsilon_0}, \quad E_{\text{cond}} = \frac{\sigma}{\epsilon_0}.$$

Here σ refers to charge per unit area on the particular conducting face, not the sum of charge densities

on two faces of a plate.

Step 5: (ii) Compare with a nonconducting sheet Take an infinite, uniformly charged nonconducting sheet with the same surface charge density σ , or a large sheet observed away from its edges. By symmetry, its field is perpendicular to the sheet and has equal magnitude on both sides. For a pillbox straddling it, flux emerges through both flat faces:

$$2E_{\text{sheet}}a = \frac{\sigma a}{\epsilon_0}, \quad E_{\text{sheet}} = \frac{\sigma}{2\epsilon_0}.$$

Comparing the magnitudes for the same positive σ ,

$$\frac{E_{\text{cond}}}{E_{\text{sheet}}} = \frac{\sigma/\epsilon_0}{\sigma/(2\epsilon_0)} = 2.$$

The factor of two arises because a conductor has zero field on the interior side, whereas a nonconducting sheet has equal field on both sides.

Step 6: Conclusion (i) For the charged spherical shell, $E = 0$ ($r < R$) and $\vec{E} = Q\hat{r}/(4\pi\epsilon_0 r^2)$ ($r > R$).
(ii) For equal surface charge density, $E_{\text{cond}} = \sigma/\epsilon_0 = 2E_{\text{sheet}}$, where $E_{\text{sheet}} = \sigma/(2\epsilon_0)$.

Quick Tip to Solve: Count the pillbox faces carrying flux: one for a conducting surface and two for a symmetric nonconducting sheet. For the shell, decide whether the Gaussian sphere encloses zero charge or the full charge before calculating the field.

32(a). (i) (1) What is meant by current sensitivity of a galvanometer? Mention the factors on which it depends.

(2) A galvanometer of resistance G is converted into a voltmeter of range $(0 - V)$ by using a resistance R . Find the resistance, in terms of R and G , required to convert it into a voltmeter of range $\left(0 - \frac{V}{2}\right)$.

(ii) The magnetic flux through a coil of resistance 5Ω increases with time as: $\phi = (2.0t^3 + 5.0t^2 + 6.0t)$ mWb. Find the magnitude of induced current through the coil at $t = 2$ s. [5 marks]

Solution:

Concept:

- In a moving-coil galvanometer with a radial magnetic field, the magnetic torque is $NIAB$ and the restoring torque is $k\theta$. Here N is the number of turns, A the coil area, B the field strength and k the torsional constant of the suspension.
- A voltmeter is formed by adding a high resistance in series with a galvanometer. At full-scale deflection its current remains I_g , so its range is I_g times its total resistance.
- Faraday's law gives the induced emf $\varepsilon = -d\phi/dt$; its magnitude divided by the coil resistance gives the induced current. Convert milliwebers to webers before using SI units.

Step 1: (i)(1) Define and derive current sensitivity Current sensitivity is the angular deflection produced per unit current through the galvanometer. At equilibrium, magnetic torque equals restoring torque:

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

Its SI unit is rad A^{-1} . Thus it increases with the number of turns, the area of the coil and the strength of the radial magnetic field, and increases when the torsional constant decreases. The radial field

makes the magnetic torque proportional to current throughout the working range.

Step 2: (i)(2) Compare the two voltmeter ranges In the original voltmeter, the external resistance R and galvanometer resistance G are in series. If R' is the new external series resistance, the same galvanometer reaches full scale at the same current I_g :

$$\begin{aligned} V &= I_g(R + G), \\ \frac{V}{2} &= I_g(R' + G), \\ R' + G &= \frac{R + G}{2}, \\ R' &= \frac{R - G}{2}. \end{aligned}$$

The total resistance must be halved; halving only the external resistance would neglect G . A nonnegative external series resistance requires $R \geq G$; if $R < G$, this lower range cannot be obtained solely by adding a passive series resistance.

Step 3: (ii) Differentiate the given flux and use Ohm's law With time measured in seconds, the given flux in webers is

$$\phi = (2.0t^3 + 5.0t^2 + 6.0t) \times 10^{-3} \text{ Wb}.$$

The induced emf depends on the instantaneous rate of change of flux, so differentiate before inserting the time:

$$\begin{aligned} |\varepsilon| &= (6.0t^2 + 10.0t + 6.0) \times 10^{-3} \text{ V}, \\ |\varepsilon|_{t=2\text{s}} &= (24 + 20 + 6) \times 10^{-3} \text{ V} \\ &= 0.050 \text{ V}, \\ |I| &= \frac{0.050}{5} = 0.010 \text{ A}. \end{aligned}$$

The negative sign in Faraday's law specifies opposition to the increasing flux; only the magnitude is requested here.

Step 4: Conclusion (i)(1) $S_I = \theta/I = NAB/k$: directly proportional to N, A, B and inversely proportional to k . (i)(2) The required external series resistance is $R' = (R - G)/2$. (ii) The induced current magnitude at $t = 2 \text{ s}$ is 10 mA .

Quick Tip to Solve: When changing a voltmeter range, scale the total resistance $R + G$. For a flux polynomial, differentiate first and remember that $1 \text{ mWb s}^{-1} = 1 \text{ mV}$.

32(b). (i) A rectangular coil of N turns and area of cross-section A is rotated at a steady angular speed ω in a uniform magnetic field. Obtain an expression for the emf induced in the coil at any instant of time.

(ii) Two coplanar and concentric circular loops L_1 and L_2 are placed coaxially with their centres coinciding. The radii of L_1 and L_2 are 1 cm and 100 cm respectively. Calculate the mutual inductance of the loops. (Take $\pi^2 = 10$)

[5 marks]

Solution:

Concept:

- The magnetic flux through a plane coil turn is $\phi = BA \cos \theta$, where θ is the angle between the field B and the normal to its area A .
- For N identical turns, Faraday's law gives $\varepsilon = -d(N\phi)/dt$. A changing orientation changes the flux even when the field magnitude is constant.
- The field at the centre of a circular loop of radius r carrying current I is $B = \mu_0 I / (2r)$. Mutual inductance is the flux linkage in one circuit per unit current in the other: $M = \Phi_{\text{linked}} / I$.

Step 1: (i) Express the flux linkage of the rotating coil Consider the usual generator arrangement, with the rotation axis in the plane of the coil and perpendicular to the uniform magnetic field of magnitude B . Choose $t = 0$ when the coil normal is parallel to the field. Rotation at constant angular speed ω then gives $\theta = \omega t$. Since every turn links the same flux,

$$N\phi = NBA \cos(\omega t).$$

The flux is maximum when the coil's plane is perpendicular to the field and is zero when its plane is parallel to the field.

Step 2: Differentiate the flux linkage to obtain the emf Apply Faraday's law to the entire coil:

$$\begin{aligned} \varepsilon(t) &= -\frac{d}{dt} [NBA \cos(\omega t)] \\ &= NBA\omega \sin(\omega t) \\ &= \varepsilon_0 \sin(\omega t), \quad \varepsilon_0 = NBA\omega. \end{aligned}$$

The induced emf alternates in sign every half revolution. It is zero at maximum flux and has maximum magnitude when the flux passes through zero. For a different initial angle θ_0 , replace ωt by $\omega t + \theta_0$; this only changes the phase, not the peak emf.

Step 3: (ii) Find the flux through the smaller loop Let $r_1 = 1 \text{ cm} = 10^{-2} \text{ m}$ and $r_2 = 100 \text{ cm} = 1 \text{ m}$. Send current I_2 through the larger loop L_2 . Since $r_1/r_2 = 0.01$, its field is approximately uniform over the small loop and equals its central value:

$$B_2 \simeq \frac{\mu_0 I_2}{2r_2}.$$

The loops are coplanar and concentric, so this field is normal to the area of L_1 . Both loops are single turns. Hence,

$$\Phi_1 \simeq B_2 \pi r_1^2 = \frac{\mu_0 I_2 \pi r_1^2}{2r_2}.$$

Step 4: Calculate the mutual inductance in SI units Divide the linked flux by the current producing it.

Using $\mu_0 = 4\pi \times 10^{-7} \text{ H m}^{-1}$ and the prescribed $\pi^2 = 10$,

$$\begin{aligned} M &= \frac{\Phi_1}{I_2} \simeq \frac{\mu_0 \pi r_1^2}{2r_2} \\ &= \frac{(4\pi \times 10^{-7})\pi(10^{-2})^2}{2(1)} \text{ H} \\ &= 2\pi^2 \times 10^{-11} \text{ H} \\ &= 2.0 \times 10^{-10} \text{ H}. \end{aligned}$$

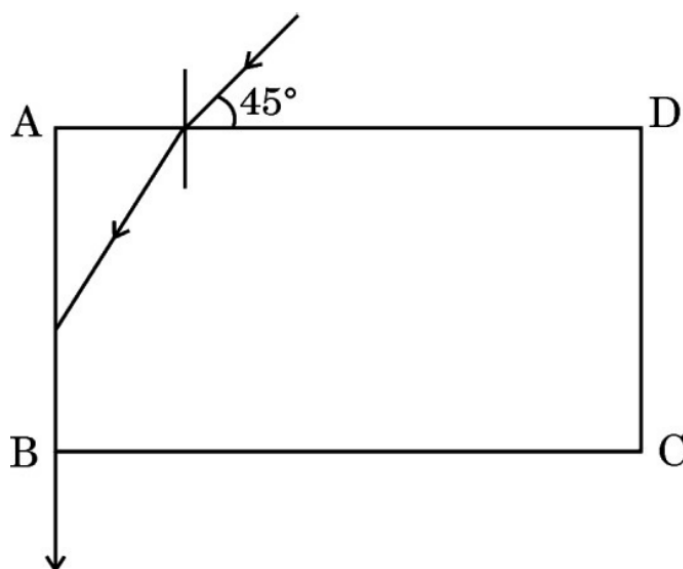
Mutual inductance has the same magnitude whichever loop carries the source current. Using the larger loop as the source is simpler because its field is nearly uniform over the smaller loop.

Step 5: Conclusion (i) The induced emf is $\varepsilon(t) = NBA\omega \sin(\omega t)$, for the stated initial orientation, with peak value $NBA\omega$. (ii) The mutual inductance is approximately $M = 2.0 \times 10^{-10} \text{ H}$, or 0.20 nH.

Quick Tip to Solve: For a rotating coil, differentiate the flux cosine to get an emf sine. For very unequal concentric loops, use the larger loop's central field and the smaller loop's area.

33(a). (i) Trace the path of a ray of light showing refraction through a triangular prism and hence obtain an expression for angle of deviation (δ) in terms of A , i and e , where symbols have their usual meanings. Draw a graph showing the variation of angle of deviation with the angle of incidence.

(ii) In the figure, a ray of light is incident on a transparent liquid contained in a thin glass box at an angle of 45° with its one face. The emergent ray passes along the face AB . Find the refractive index of the liquid. [5 marks]



Solution:

Concept:

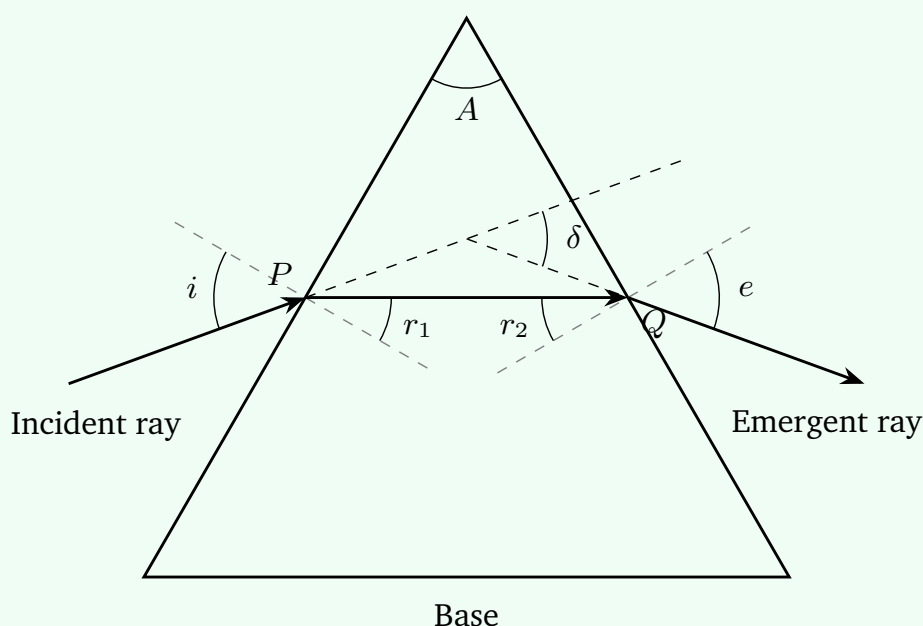
- For a prism of angle A , let i, e be the angles of incidence and emergence, and r_1, r_2 the refraction angles inside it. All four angles are measured from the respective face normals.
- Snell's law at an air-liquid boundary is $\sin i = \mu \sin r$, where μ is the refractive index of the liquid relative to air.

- At the critical angle C , light travels from liquid to air with refraction angle 90° ; hence $\mu \sin C = 1$.

Step 1: (i) Ray path and geometry inside the prism The incident ray bends towards the normal at the first face and away from the normal at the second face. The total deviation is towards the base of the prism. In the labelled diagram, P and Q are the points of entry and emergence; the dashed lines through them are the face normals. The upper dashed continuations show the change between the original and final ray directions. The diagram uses a symmetric ray path for clarity, while the following derivation applies to any transmitted ray.

The two normals and the two prism faces form a quadrilateral whose angles at the faces are each 90° . Thus the angle between the inward normal segments is $180^\circ - A$. In the triangle made by these segments and the internal ray,

$$r_1 + r_2 + (180^\circ - A) = 180^\circ, \quad r_1 + r_2 = A.$$



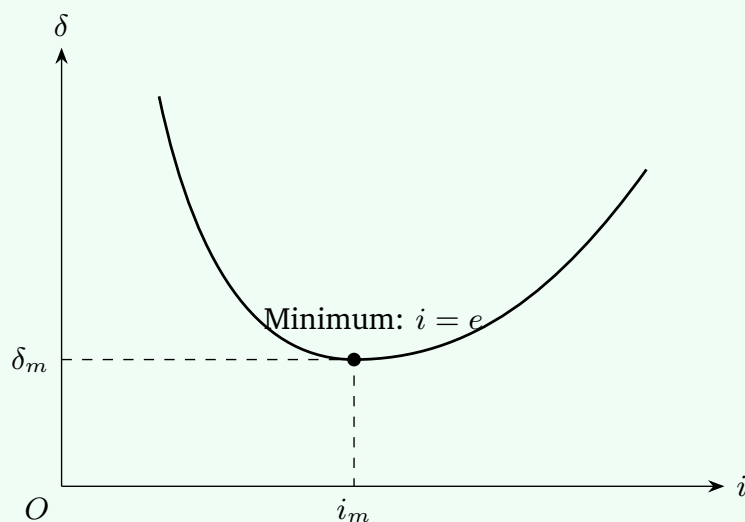
Refraction through a prism; angles are measured from the dashed normals.

Step 2: (i) Add the deviations at the two faces At the first face the ray turns through $i - r_1$. At the second face it turns through $e - r_2$ in the same overall sense. Therefore,

$$\begin{aligned} \delta &= (i - r_1) + (e - r_2) \\ &= i + e - (r_1 + r_2) = i + e - A. \end{aligned}$$

This relation follows from geometry; no assumption of minimum deviation is required for it.

Step 3: (i) Deviation versus incidence For a fixed prism and wavelength, increasing i initially decreases δ . It reaches a minimum value δ_m , then increases. The plotted curve shows this behaviour over the range in which a ray emerges from the second face. At the minimum, the light path is symmetric, so $i = e = i_m$ and $r_1 = r_2 = A/2$. Substituting in the deviation relation gives $\delta_m = 2i_m - A$. The curve need not be symmetric about its lowest point.



Variation of deviation with incidence for a fixed prism and wavelength.

Step 4: (ii) Apply Snell's law at the top face of the liquid The given 45° is measured from the top face AD , so the incidence angle from its normal is $i = 90^\circ - 45^\circ = 45^\circ$. Let r be the angle inside the liquid from the normal to AD . The thin glass walls are treated as parallel layers: their intermediate refractions cancel in the net air-liquid relation. Therefore,

$$\sin 45^\circ = \mu \sin r, \quad \mu \sin r = \frac{1}{\sqrt{2}}.$$

Step 5: (ii) Use grazing emergence at the adjacent face The normal to AD is perpendicular to the normal to AB . Hence the incidence angle at AB is $90^\circ - r$. The emergent ray travels along AB , making 90° with its normal; thus this incidence angle equals the critical angle C . Consequently,

$$C = 90^\circ - r, \quad \mu \sin C = 1, \quad \mu \cos r = 1.$$

Squaring and adding this equation and the first-face equation eliminates the unknown ray angle:

$$\begin{aligned} \mu^2(\sin^2 r + \cos^2 r) &= \frac{1}{2} + 1, \\ \mu^2 &= \frac{3}{2}. \end{aligned}$$

The positive root is used because the liquid has an ordinary positive refractive index; the result is dimensionless.

Step 6: Conclusion For the prism, $\delta = i + e - A$; the deviation curve has a minimum δ_m at $i = e$. For the liquid, $\mu = \sqrt{3/2} \approx 1.225$.

Quick Tip to Solve: For grazing emergence from the next perpendicular face, pair $\mu \sin r = \sin i$ with $\mu \cos r = 1$; square and add to remove r immediately.

33(b). (i) The displacement of two light waves, each of amplitude 'a' and frequency ω , emanating from two coherent sources of light, are given by $y_1 = a \cos \omega t$ and $y_2 = a \cos(\omega t + \phi)$. ϕ is the phase difference between the two waves. These light waves superpose at a point. Obtain the expression for the resultant intensity at that point.

(ii) In Young's double slit experiment, find the ratio of intensities at two points on a screen when waves emanating from two slits reaching these points have path differences (i) $\frac{\lambda}{6}$ and (ii) $\frac{\lambda}{12}$. [5 marks]

Solution:

Concept:

- The principle of superposition gives the resultant displacement as the algebraic sum of the two displacements at the observation point. Coherent sources maintain a constant phase difference ϕ .
- Intensity is proportional to the square of the wave amplitude. Write $I_0 = Ka^2$ for the intensity due to either slit alone, where K is the same proportionality constant for both waves.
- A path difference Δ corresponds to the phase difference $\phi = 2\pi\Delta/\lambda$, where λ is the wavelength. Thus the phase used in the interference formula must be calculated from the path difference.

Step 1: (i) Add the two wave displacements At the observation point, the resultant displacement is

$$\begin{aligned} y &= y_1 + y_2 \\ &= a \cos \omega t + a \cos(\omega t + \phi) \\ &= 2a \cos \frac{\phi}{2} \cos \left(\omega t + \frac{\phi}{2} \right). \end{aligned}$$

Here we used $\cos A + \cos B = 2 \cos[(A+B)/2] \cos[(A-B)/2]$. The resultant wave has the same angular frequency as the individual waves; its amplitude is $A = 2a |\cos(\phi/2)|$. The absolute value makes the amplitude non-negative and does not affect the intensity.

Step 2: (i) Convert the resultant amplitude into intensity Squaring the resultant amplitude and using $I_0 = Ka^2$ gives

$$\begin{aligned} I &= KA^2 = 4Ka^2 \cos^2 \frac{\phi}{2} \\ &= 4I_0 \cos^2 \frac{\phi}{2} = 2I_0(1 + \cos \phi). \end{aligned}$$

The interference term $2I_0 \cos \phi$ accounts for the change from the sum of the two separate intensities. For phase difference $2n\pi$, the waves reinforce and $I_{\max} = 4I_0$; for $(2n+1)\pi$, they cancel and $I_{\min} = 0$. These limits verify the expression for two equal-amplitude waves.

Step 3: (ii) Evaluate the intensity for the first path difference For the point with path difference $\Delta_1 = \lambda/6$, the phase difference is

$$\phi_1 = \frac{2\pi \lambda}{\lambda} \frac{\lambda}{6} = \frac{\pi}{3}.$$

Hence its intensity is

$$I_1 = 4I_0 \cos^2 \frac{\pi}{6} = 4I_0 \left(\frac{\sqrt{3}}{2} \right)^2 = 3I_0.$$

Step 4: (ii) Evaluate the intensity for the second path difference The official paper gives $\Delta_2 = \lambda/12$. Its phase difference is

$$\phi_2 = \frac{2\pi}{\lambda} \frac{\lambda}{12} = \frac{\pi}{6}.$$

Using the half-angle identity avoids approximating the trigonometric value:

$$\begin{aligned} I_2 &= 4I_0 \cos^2 \frac{\pi}{12} \\ &= 2I_0 \left(1 + \cos \frac{\pi}{6} \right) \\ &= (2 + \sqrt{3})I_0. \end{aligned}$$

Both points lie between the central maximum and the first minimum. The second point has the smaller path difference, so its larger intensity is consistent with the interference pattern. The common single-slit intensity cancels when the ratio is formed.

Step 5: Conclusion (i) The resultant intensity is $I = 4I_0 \cos^2(\phi/2) = 2I_0(1 + \cos \phi)$, where I_0 is the intensity due to either wave alone. (ii) In the order of the stated path differences, the ratio is

$$I_{\lambda/6} : I_{\lambda/12} = 3 : (2 + \sqrt{3}).$$

Quick Tip to Solve: For equal slit intensities, substitute the path difference directly in $I = 4I_0 \cos^2(\pi\Delta/\lambda)$; the cosine argument is half the phase difference. Keep the given order when writing the intensity ratio.