

CBSE Class 12 Physics Question Paper 2024 with Solution PDF-Set 55/4/2



Question Paper with Solutions

Conducted by the Central Board of Secondary Education (CBSE)

Time Allowed: 3 hours

Maximum Marks: 70

General Instructions

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

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

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

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

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

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

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

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

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

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

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

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

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

Section A (16 marks)

1. Three point charges, each of charge q are placed on vertices of a triangle ABC , with $AB = AC = 5L$, $BC = 6L$. The electrostatic potential at midpoint of side BC will be [1 mark]

- (A) $\frac{11q}{48\pi\epsilon_0 L}$
(B) $\frac{8q}{36\pi\epsilon_0 L}$
(C) $\frac{5q}{24\pi\epsilon_0 L}$
(D) $\frac{q}{16\pi\epsilon_0 L}$

Correct Answer: (A) $\frac{11q}{48\pi\epsilon_0 L}$

Solution:

Concept:

- The potential of a point charge is $V = kq/r$, where $k = 1/(4\pi\epsilon_0)$ and r is its distance from the observation point.
- Electric potential is a scalar, so contributions from all three charges add algebraically; no vector components are needed.

Step 1: Find the distances from the midpoint Let M be the midpoint of BC. Then $BM = CM = 3L$. Since $AB = AC$, AM is perpendicular to BC. Pythagoras' theorem in triangle ABM gives

$$AM = \sqrt{(5L)^2 - (3L)^2} = 4L.$$

Step 2: Add all three potentials Each charge is the same signed charge q . Thus the two base charges contribute equally, while the apex charge is farther away:

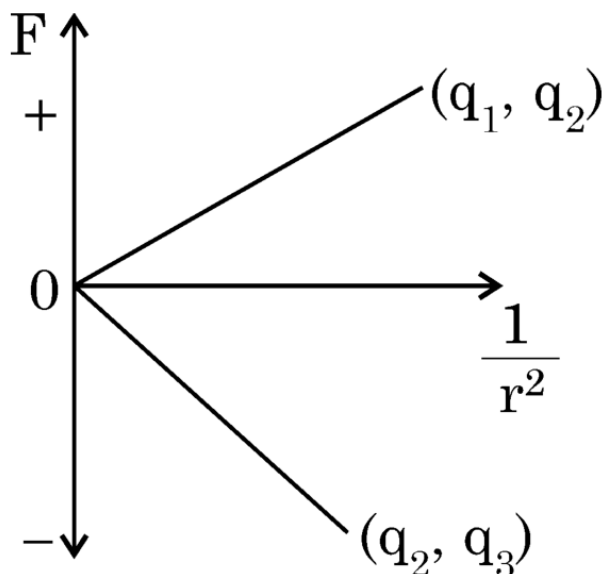
$$V_M = \frac{q}{4\pi\epsilon_0} \left(\frac{1}{4L} + \frac{1}{3L} + \frac{1}{3L} \right) = \frac{q}{4\pi\epsilon_0 L} \frac{11}{12}.$$

Option (D) includes only the apex contribution. Options (B) and (C) do not equal the sum of the three inverse distances.

Step 3: Conclusion $V_M = \frac{11q}{48\pi\epsilon_0 L}$. Hence, the correct option is (A).

Quick Tip to Solve: Recognise the 3-4-5 right triangle at the midpoint, then add potentials as scalars rather than resolving fields.

2. The Coulomb force (F) versus ($1/r^2$) graphs for two pairs of point charges (q_1 and q_2) and (q_2 and q_3) are shown in the figure. The charge q_2 is positive and has least magnitude. Then [1 mark]



- (A) $q_1 > q_2 > q_3$
- (B) $q_1 > q_3 > q_2$
- (C) $q_3 > q_2 > q_1$
- (D) $q_3 > q_1 > q_2$

Correct Answer: (A) $q_1 > q_2 > q_3$

Solution:

Concept:

- For signed radial Coulomb force, $F = kq_iq_j/r^2$; the slope of an F versus $1/r^2$ graph is kq_iq_j , with $k > 0$.
- A positive slope indicates like charges and a negative slope indicates unlike charges. Signed charge order differs from order of charge magnitudes.

Step 1: Determine the signs from the two slopes The line for (q_1, q_2) has positive slope, so $q_1q_2 > 0$. Since $q_2 > 0$, $q_1 > 0$. The line for (q_2, q_3) has negative slope, so $q_2q_3 < 0$ and therefore $q_3 < 0$.

Step 2: Use the least-magnitude condition The given condition implies $|q_1| > |q_2|$. Both these charges are positive, hence $q_1 > q_2$. Every positive charge is greater algebraically than a negative charge, so $q_2 > q_3$. Options (B), (C) and (D) all place the negative charge q_3 above at least one positive charge and are inconsistent with the slopes.

Step 3: Conclusion The signed charge order is $q_1 > q_2 > q_3$. Hence, the correct option is (A).

Quick Tip to Solve: Read the signs of the slopes first; use the least-magnitude statement only after identifying the positive charges.

3. The magnetic susceptibility for a diamagnetic material is

[1 mark]

- (A) small and negative
- (B) small and positive
- (C) large and negative
- (D) large and positive

Correct Answer: (A) small and negative

Solution:

Concept:

- Magnetic susceptibility χ_m relates magnetisation M to magnetising field H by $M = \chi_m H$; it is dimensionless.
- In a diamagnetic material the induced magnetic moment opposes the applied field, and the induced response is weak.

Step 1: Determine the sign of susceptibility Choose the applied field as the positive direction. The induced magnetisation in a diamagnetic specimen points in the opposite direction. Therefore $M/H < 0$, making susceptibility negative. This rules out both positive alternatives (B) and (D).

Step 2: Determine the magnitude of the response Ordinary diamagnetic materials are weakly repelled by a magnet: their induced magnetisation is small compared with the applied magnetising field. Thus $|\chi_m| \ll 1$. A large negative susceptibility, option (C), does not describe ordinary diamagnetism in the Class 12 classification.

Step 3: Conclusion Magnetic susceptibility is small and negative for a diamagnetic material. Hence, the correct option is (A).

Quick Tip to Solve: For diamagnetism, remember two separate facts: opposing magnetisation sets the negative sign and weak response sets the small magnitude.

4. A circular loop A of radius R carries a current I . Another circular loop B of radius $r \left(= \frac{R}{20} \right)$ is placed concentrically in the plane of A. The magnetic flux linked with loop B is proportional to [1 mark]

- (A) R
- (B) $\sqrt{R}$
- (C) $R^{3/2}$
- (D) R^2

Correct Answer: (A) R

Solution:

Concept:

- The magnetic field at the centre of a circular current loop is $B = \mu_0 I / (2R)$, where R is the loop radius and I is its current.
- Magnetic flux is $\Phi = \int \vec{B} \cdot d\vec{A}$. A much smaller concentric coplanar loop samples an approximately uniform perpendicular field, so $\Phi \simeq BA$.

Step 1: Evaluate the field and the receiving area Loop B has radius $r = R/20$, so it lies close to the

centre of loop A. For fixed current I , the field there scales as R^{-1} . Its area is

$$A_B = \pi r^2 = \frac{\pi R^2}{400}.$$

The field is perpendicular to the plane, so its angle with the area normal is zero when their positive directions coincide.

Step 2: Combine the two radius dependences Multiplying the nearly uniform field by the area gives the flux magnitude:

$$|\Phi_B| \simeq \frac{\mu_0 I}{2R} \frac{\pi R^2}{400} = \frac{\mu_0 \pi I R}{800}.$$

Thus the area contributes two powers of R , while the field removes one. Option (D) incorrectly treats the field as constant; neither fractional power in (B) or (C) follows from these factors. The exact field variation changes the numerical coefficient, but not this scaling for fixed r/R .

Step 3: Conclusion At fixed current, the magnetic flux linked with loop B is proportional to R . Hence, the correct option is (A).

Quick Tip to Solve: Track both factors: the source loop gives $B \propto 1/R$, while the receiving loop gives area $\propto R^2$.

5. A particle of mass m and charge q is moving with velocity $\vec{v} = v_x \hat{i} + v_y \hat{j}$. If it is subjected to a magnetic field $\vec{B} = B_0 \hat{i}$, it will move in a [1 mark]

- (A) straight line path
- (B) circular path
- (C) helical path
- (D) parabolic path

Correct Answer: (C) helical path

Solution:

Concept:

- The magnetic force on a moving charge is $\vec{F} = q\vec{v} \times \vec{B}$. It acts only on the velocity component perpendicular to the field and does no work.
- A parallel velocity component remains constant; the perpendicular component produces circular motion with radius $r = m|v_\perp|/(|q|B)$.

Step 1: Resolve the motion relative to the field The magnetic field is along the x-axis. Hence $v_x \hat{i}$ is parallel to it and $v_y \hat{j}$ is perpendicular. Initially,

$$\vec{F} = q(v_x \hat{i} + v_y \hat{j}) \times B_0 \hat{i} = -qB_0 v_y \hat{k}.$$

There is no x-component of force, so motion along the field continues uniformly.

Step 2: Combine the simultaneous motions The perpendicular velocity turns continuously in the yz-plane with constant magnitude, producing circular transverse motion. Adding uniform translation along x gives a helix about the x-axis, for the two nonzero components indicated in the question. A straight path requires zero perpendicular component, while a circle requires zero parallel component. A parabola requires a fixed acceleration direction, unlike the continually rotating magnetic force.

Step 3: Conclusion The particle follows a helical path about the magnetic-field direction. Hence, the correct option is (C).

Quick Tip to Solve: Identify velocity parallel and perpendicular to the field: both present means a helix, parallel alone a line, and perpendicular alone a circle.

6. The quantum nature of light explains the observations on photoelectric effect as

[1 mark]

- (A) there is a minimum frequency of incident radiation below which no electrons are emitted.
- (B) the maximum kinetic energy of photoelectrons depends only on the frequency of incident radiation.
- (C) when the metal surface is illuminated, electrons are ejected from the surface after sometime.
- (D) the photoelectric current is independent of the intensity of incident radiation.

Correct Answer: Both (A) and (B) are correct for a fixed metal; the printed question has no unique correct option.

Solution:

Concept:

- A photon of frequency ν carries energy $h\nu$. One absorbed photon transfers its energy to one electron.
- Einstein's photoelectric equation is $K_{\max} = h\nu - \phi$, where ϕ is the metal's work function. The threshold frequency is $\nu_0 = \phi/h$.

Step 1: Test the threshold and energy statements If $\nu < \nu_0$, a photon has insufficient energy to overcome the work function, so no photoelectron is emitted in the usual photoelectric experiment. Statement (A) is therefore correct. For the same metal, ϕ is fixed, and Einstein's equation shows that $K_{\max}$ depends on incident frequency, not intensity. Thus (B) is also correct under the standard fixed-metal interpretation.

Step 2: Test the delay and current statements Photoemission begins practically instantaneously when light of adequate frequency falls on the metal; there is no measurable waiting time for energy accumulation. Hence (C) is false. At fixed frequency above threshold, increasing intensity supplies more photons per second and increases the emitted-electron rate and saturation current, so (D) is false. Since both (A) and (B) are supported by the quantum account, selecting a unique option would hide an ambiguity in the printed alternatives.

Step 3: Conclusion Both options (A) and (B) describe observations explained by the quantum nature of light for a fixed metal. The printed question is ambiguous as a single-choice MCQ.

Quick Tip to Solve: Use $h\nu$ to check threshold and maximum energy; use photon arrival rate to check intensity and photoelectric current.

7. The phase difference between electric field $\vec{E}$ and magnetic field $\vec{B}$ in an electromagnetic wave propagating along z -axis is [1 mark]

(A) zero

(B) π

(C) $\frac{\pi}{2}$

(D) $\frac{\pi}{4}$

Correct Answer: (A) zero

Solution:

Concept:

- In a travelling electromagnetic wave, the electric and magnetic fields are mutually perpendicular and both are transverse to propagation.
- The fields oscillate in phase. In vacuum their instantaneous magnitudes satisfy $E = cB$, where c is the speed of light.

Step 1: Write the two travelling fields For propagation along the positive z -axis, choose the electric field along x and the magnetic field along y . Their oscillations can be written as

$$\vec{E} = E_0 \cos(kz - \omega t)\hat{i}, \quad \vec{B} = B_0 \cos(kz - \omega t)\hat{j},$$

where $E_0 = cB_0$. Both expressions have exactly the same phase argument.

Step 2: Distinguish phase from spatial orientation At any fixed position, both fields reach their maxima, minima and zeros simultaneously, so their phase difference is zero. Their perpendicular directions do not imply a phase difference of $\pi/2$; that angle describes orientation in space. A phase difference of π would put maxima and minima out of step, and $\pi/4$ would introduce a time offset, neither of which occurs here.

Step 3: Conclusion The electric and magnetic fields have phase difference $\Delta\phi = 0$. Hence, the correct option is (A).

Quick Tip to Solve: In an electromagnetic wave, keep the two facts separate: fields are perpendicular in space but synchronous in time.

8. The radius (r_n) of n^{th} orbit in Bohr model of hydrogen atom varies with n as [1 mark]

(A) $r_n \propto n$

(B) $r_n \propto \frac{1}{n}$

(C) $r_n \propto n^2$

(D) $r_n \propto \frac{1}{n^2}$

Correct Answer: (C) $r_n \propto n^2$

Solution:

Concept:

- In the Bohr model, Coulomb attraction provides the centripetal force: $m_e v_n^2 / r_n = k e^2 / r_n^2$, where $k = 1/(4\pi\epsilon_0)$.
- Angular momentum is quantised: $m_e v_n r_n = n\hbar$, where n is the principal quantum number.

Step 1: Eliminate the orbital speed Substitute $v_n = n\hbar/(m_e r_n)$ in the force equation and rearrange:

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

The factor multiplying n^2 is constant for hydrogen.

Step 2: Compare the proposed dependences The orbital radius grows quadratically with n : doubling n makes the radius four times as large. Option (A) predicts only a twofold increase, whereas (B) and (D) incorrectly predict a decrease.

Step 3: Conclusion $r_n \propto n^2$. Hence, the correct option is (C).

Quick Tip to Solve: Remember $r_n = a_0 n^2$ for hydrogen; the inverse-square dependence belongs to the magnitude of orbital energy.

9. An ac source $V = 282 \sin(100t)$ volt is connected across a $1 \mu\text{F}$ capacitor. The rms value of current in the circuit will be (take $\sqrt{2} = 1.41$) [1 mark]

- (A) 10 mA
- (B) 20 mA
- (C) 40 mA
- (D) 80 mA

Correct Answer: (B) 20 mA

Solution:

Concept:

- For $V = V_0 \sin \omega t$, V_0 is peak voltage and $V_{\text{rms}} = V_0/\sqrt{2}$.
- Capacitive reactance is $X_C = 1/(\omega C)$; thus $I_{\text{rms}} = V_{\text{rms}}/X_C$.

Step 1: Identify the circuit values From the supplied voltage, $V_0 = 282 \text{ V}$ and $\omega = 100 \text{ rad s}^{-1}$. Also $C = 1 \mu\text{F} = 10^{-6} \text{ F}$. Hence

$$V_{\text{rms}} = \frac{282}{1.41} = 200 \text{ V}, \quad X_C = \frac{1}{100 \times 10^{-6}} = 10^4 \Omega.$$

Step 2: Calculate the rms current Apply the ac form of Ohm's law:

$$I_{\text{rms}} = \frac{200}{10^4} = 0.020 \text{ A} = 20 \text{ mA}.$$

The other listed currents do not satisfy $I_{\text{rms}} = \omega C V_{\text{rms}}$. In particular, 282 V is the peak voltage, so using it directly would give the peak current instead.

Step 3: Conclusion $I_{\text{rms}} = 20 \text{ mA}$. Hence, the correct option is (B).

Quick Tip to Solve: Read ω directly from the sine argument and divide the voltage amplitude by $\sqrt{2}$ before calculating rms current.

10. A galvanometer of resistance $100\ \Omega$ is converted into an ammeter of range (0–1 A) using a resistance of $0.1\ \Omega$. The ammeter will show full scale deflection for a current of about [1 mark]

- (A) 0.1 mA
- (B) 1 mA
- (C) 10 mA
- (D) 0.1 A

Correct Answer: No printed option gives the ammeter full-scale current of 1 A; (B) instead gives the galvanometer current.

Solution:

Concept:

- An ammeter of range 0–1 A reaches full scale at total current $I = 1\ \text{A}$.
- For a galvanometer of resistance G shunted by S , equal parallel voltages give $I_g G = (I - I_g)S$, where I_g is galvanometer current.

Step 1: Check the quantity actually requested The printed question asks for full-scale current of the ammeter, whose stated range already fixes that current at 1 A. None of (A), (B), (C), or (D) equals this value. Thus the wording and the options do not define a correct listed answer.

Step 2: Identify the likely intended calculation If the intended quantity is the galvanometer's full-scale current, use $G = 100\ \Omega$ and $S = 0.1\ \Omega$:

$$I_g = \frac{IS}{G + S} = \frac{1 \times 0.1}{100.1}\ \text{A} \simeq 1.0\ \text{mA}.$$

This is option (B), but it is the current in the galvanometer branch, not the total current entering the ammeter. The shunt carries nearly all the remaining current.

Step 3: Conclusion As printed, the ammeter reaches full scale at 1 A, which is absent from the options. Option (B), 1 mA, is the likely intended answer only for the galvanometer current.

Quick Tip to Solve: Distinguish the ammeter's total current I from the small galvanometer branch current I_g before using the shunt formula.

11. In Balmer series of hydrogen atom, as the wavelength of spectral lines decreases, they appear [1 mark]

- (A) equally spaced and equally intense.
- (B) further apart and stronger in intensity.
- (C) closer together and stronger in intensity.
- (D) closer together and weaker in intensity.

Correct Answer: (D) closer together and weaker in intensity.

Solution:

Concept:

- Balmer lines arise from transitions $n \rightarrow 2$, with $n = 3, 4, 5, \dots$. Their wavelengths obey $1/\lambda = R_H(1/4 - 1/n^2)$.
- As the upper level increases, Balmer lines approach the series limit and become progressively weaker in the usual hydrogen emission spectrum.

Step 1: Examine the separation of successive lines Increasing n decreases $1/n^2$, so $1/\lambda$ increases toward $R_H/4$ and the wavelength decreases toward $4/R_H$. Successive changes become smaller, so the lines crowd together near the short-wavelength limit; they are neither equally spaced nor increasingly far apart.

Step 2: Examine the intensity trend In the usual Balmer spectrum, successive higher-member lines become weaker toward the series limit. Crowding does not mean that each individual line becomes stronger. Consequently (A) and (B) have the wrong spacing trend, and (C) has the wrong intensity trend.

Step 3: Conclusion The lines appear closer together and weaker in intensity as wavelength decreases. Hence, the correct option is (D).

Quick Tip to Solve: At the short-wavelength end of a hydrogen series, remember convergence: the higher-member lines crowd together and become faint.

12. A coil of N turns is placed in a magnetic field $\vec{B}$ such that $\vec{B}$ is perpendicular to the plane of the coil. $\vec{B}$ changes with time as $B = B_0 \cos\left(\frac{2\pi}{T}t\right)$ where T is the time period. The magnitude of emf induced in the coil will be maximum at

Here, $n = 1, 2, 3, 4, \dots$

[1 mark]

(A) $t = \frac{nT}{8}$

(B) $t = \frac{nT}{4}$

(C) $t = \frac{nT}{2}$

(D) $t = nT$

Correct Answer: Option (B) requires odd n , whereas the paper specifies all positive integers; exact maxima occur at $(2k+1)T/4$.

Solution:

Concept:

- For field normal to a coil of area A , the flux linkage is NAB . Faraday's law gives $\varepsilon = -NA dB/dt$.
- The magnitude of a sine is greatest when its argument is an odd multiple of $\pi/2$.

Step 1: Differentiate the changing magnetic field Using the printed field variation,

$$\varepsilon = \frac{2\pi NAB_0}{T} \sin\left(\frac{2\pi t}{T}\right).$$

Thus the emf magnitude is maximum at

$$\frac{2\pi t}{T} = \frac{(2k+1)\pi}{2}, \quad t = \frac{(2k+1)T}{4}, \quad k = 0, 1, 2, \dots$$

These times are $T/4, 3T/4, 5T/4, \dots$

Step 2: Test the printed integer condition The paper explicitly gives $n = 1, 2, 3, 4, \dots$. Option (B), $nT/4$, includes zero-emf times such as $T/2$ when $n = 2$, so it is correct only with odd n . Option (A) includes $T/8$, where the sine is $1/\sqrt{2}$, not its maximum. Options (C) and (D) give zero emf for all their listed integer values.

Step 3: Conclusion The exact times are $t = (2k + 1)T/4$, $k = 0, 1, 2, \dots$. No option is fully correct with the printed unrestricted positive integer n . The intended option is (B), provided n is restricted to odd values.

Quick Tip to Solve: For maximum emf, maximise $|dB/dt|$, not $|B|$; check that a proposed time sequence includes only odd quarter-periods.

13. Assertion (A): In interference and diffraction of light, light energy reduces in one region producing a dark fringe. It increases in another region and produces a bright fringe.

Reason (R): This happens because energy is not conserved in the phenomena of interference and diffraction. [1 mark]

- (A) If both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of Assertion (A).
(B) If both Assertion (A) and Reason (R) are true and Reason (R) is not the correct explanation of Assertion (A).
(C) If Assertion (A) is true and Reason (R) is false.
(D) If both Assertion (A) and Reason (R) are false.

Correct Answer: (C) If Assertion (A) is true and Reason (R) is false.

Solution:

Concept:

- Interference and diffraction redistribute the intensity of light through superposition of wave amplitudes.
- Energy is conserved: reduction of intensity in dark regions is accompanied by enhancement in bright regions.

Step 1: Evaluate the assertion The assertion is true. Destructive superposition reduces the resultant amplitude and intensity in a dark fringe, whereas constructive superposition increases them in a bright fringe. For example, equal coherent waves can give zero intensity at a minimum and four times the single-wave intensity at a maximum.

Step 2: Evaluate the reason The reason is false. Energy is not destroyed at a dark fringe or created at a bright one. It is redistributed across the pattern, and the total outgoing energy, summed over the complete pattern, equals the energy supplied by the incident light.

Step 3: Check the explanatory link Since the reason incorrectly denies energy conservation, it cannot explain the true assertion. Options (A) and (B) require a true reason; option (D) incorrectly makes the assertion false.

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

Quick Tip to Solve: When dark and bright fringes are discussed, separate local intensity changes from total energy: redistribution preserves the total.

14. Assertion (A): When electrons drift in a conductor, it does not mean that all free electrons in the conductor are moving in the same direction.

Reason (R): The drift velocity is superposed over large random velocities of electrons. [1 mark]

(A) If both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of Assertion (A).
(B) If both Assertion (A) and Reason (R) are true and Reason (R) is not the correct explanation of Assertion (A).

(C) If Assertion (A) is true and Reason (R) is false.

(D) If both Assertion (A) and Reason (R) are false.

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

Solution:

Concept:

- Free electrons in a conductor have large random velocities whose vector average is zero without an applied electric field.
- An applied field produces a small mean drift velocity $\vec{v}_d$ superposed on random motion; conventional current is opposite to electron drift.

Step 1: Evaluate the assertion The assertion is true. A nonzero average electron drift does not mean that every electron has an instantaneous velocity in the drift direction. Electrons still have random velocity components in different directions, and collisions continually change those components.

Step 2: Evaluate the reason The reason is true. An electron's velocity may be described as a random contribution plus the small drift contribution. On averaging over many electrons, the random contributions cancel while the drift contribution remains, producing a net current.

Step 3: Check whether the reason explains the assertion The survival of large random velocities alongside the small common drift directly explains why all electrons need not move in the same direction. Thus (B) wrongly denies the explanatory link, while (C) and (D) wrongly declare one or both statements false.

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

Quick Tip to Solve: Drift velocity is an average: do not confuse a nonzero average velocity with identical instantaneous motion of every electron.

15. Assertion (A): Electrons are ejected from the surface of zinc when it is irradiated by yellow light.
Reason (R): Energy associated with a photon of yellow light is more than the work function of zinc. [1 mark]

- (A) If both Assertion (A) and Reason (R) are true and Reason (R) is the correct explanation of Assertion (A).
(B) If both Assertion (A) and Reason (R) are true and Reason (R) is not the correct explanation of Assertion (A).
(C) If Assertion (A) is true and Reason (R) is false.
(D) If both Assertion (A) and Reason (R) are false.

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

Solution:

Concept:

- Photoelectric emission requires the incident photon energy $h\nu$ to be at least the metal's work function ϕ , the minimum energy required to remove an electron.
- Photon energy is $E = hc/\lambda$. Yellow light has lower frequency and lower photon energy than the ultraviolet light needed for photoelectric emission from zinc.

Step 1: Judge the assertion Ordinary yellow light does not eject photoelectrons from a zinc surface because its frequency is below zinc's threshold frequency. Increasing the intensity supplies more such photons but does not increase the energy per photon. Therefore, Assertion (A) is false.

Step 2: Judge the reason The energy of a yellow-light photon is less than the work function of zinc, so it cannot free an electron. The reason states the opposite energy inequality and is therefore false.

Step 3: Check the explanation and codes Since both statements are false, the reason cannot correctly explain the assertion. Options (A) and (B) require two true statements, while (C) requires a true assertion; none agrees with the threshold condition.

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

Quick Tip to Solve: For zinc, check the threshold frequency first: visible yellow light cannot cause emission merely by increasing its intensity.

16. Assertion (A): The temperature coefficient of resistance is positive for metals and negative for *p*-type semiconductors.

Reason (R): The charge carriers in metals are negatively charged, whereas the majority charge carriers in *p*-type semiconductors are positively charged. [1 mark]

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

(B) If both Assertion (A) and Reason (R) are true and Reason (R) is not the correct explanation of Assertion (A).

(C) If Assertion (A) is true and Reason (R) is false.

(D) If both Assertion (A) and Reason (R) are false.

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

Solution:

Concept:

- The temperature coefficient indicates the sign of the change of resistance with temperature: a positive coefficient means resistance increases on heating.
- Conductivity depends on carrier density and mobility. For a semiconductor, $\sigma = e(n\mu_e + p\mu_h)$, where n, p are the electron and hole densities and μ_e, μ_h their mobilities.

Step 1: Judge the assertion In metals, heating increases lattice vibrations and electron scattering, raising resistance. In a semiconductor, the increase in thermally generated carriers produces the usual decrease in resistance on heating. Thus, in the standard temperature behaviour considered here, the assertion is true.

Step 2: Judge the reason Metals conduct mainly through negatively charged free electrons. In a *p*-type semiconductor, holes are the majority carriers and behave as positive charges. These statements about the carrier signs are correct, so the reason is true.

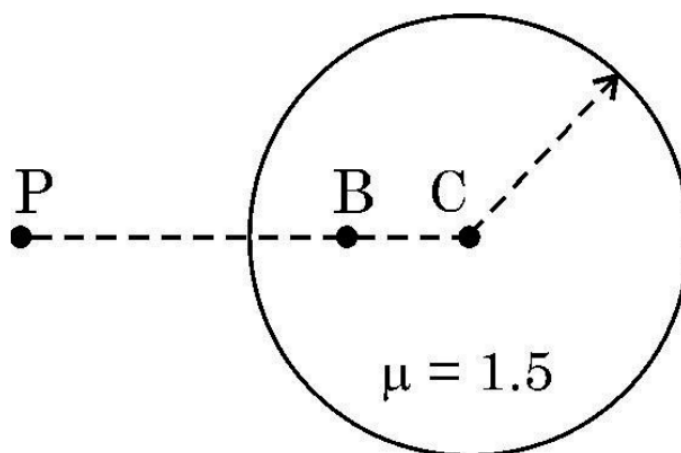
Step 3: Test the causal connection The sign of a carrier's charge does not determine the temperature coefficient. The temperature dependence follows from changes in carrier density and mobility. An *n*-type semiconductor also has a negative temperature coefficient despite its majority carriers being electrons. Thus the reason does not explain the assertion; option (A) incorrectly claims a causal connection, and (C) and (D) incorrectly reject true statements.

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

Quick Tip to Solve: Separate carrier sign from temperature dependence: compare scattering in metals with carrier generation in semiconductors.

Section B (10 marks)

17(a). An air bubble is trapped at point B ($CB = 20$ cm) in a glass sphere of radius 40 cm and refractive index 1.5, as shown in the figure. Find the nature and position of the image of this bubble as seen by an observer at point P. [2 marks]



Solution:

Concept:

- Refraction at a spherical surface obeys $n_2/v - n_1/u = (n_2 - n_1)/R$, where u, v, R are signed distances from the pole and n_1, n_2 are the incident and refracted medium indices.
- Choose the direction of incident light, from the bubble towards the observer, as positive. A negative image distance then denotes a virtual image on the incident-medium side.

Step 1: Identify the surface and signed distances Let S be the left-hand surface nearest observer P . Light from bubble B travels through glass and emerges into air at S . Since $SC = 40$ cm and $CB = 20$ cm, the bubble is $SB = 20$ cm inside this surface. Taking leftwards as positive gives

$$u = -20 \text{ cm}, \quad R = -40 \text{ cm}, \quad n_1 = 1.5, \quad n_2 = 1.$$

Both the bubble and centre of curvature lie to the right of S , hence both distances are negative.

Step 2: Substitute in the refraction formula For paraxial rays emerging through this surface,

$$\begin{aligned} \frac{1}{v} - \frac{1.5}{-20} &= \frac{1 - 1.5}{-40}, \\ \frac{1}{v} + \frac{3}{40} &= \frac{1}{80}, \\ \frac{1}{v} &= -\frac{5}{80} \text{ cm}^{-1}. \end{aligned}$$

The negative value means that the emerging rays diverge and their backward extensions meet inside the glass; they do not form a real image outside the sphere.

Step 3: Conclusion The image is virtual, with $v = -16$ cm: it appears 16 cm inside the near surface, or 24 cm from C towards P .

Quick Tip to Solve: Measure the bubble distance from the surface facing the observer, not from the centre; here it is $40 - 20 = 20$ cm.

17(b). In normal adjustment, for a refracting telescope, the distance between objective and eyepiece lens is 1.00 m. If the magnifying power of the telescope is 19, find the focal length of the objective and the eyepiece lens. [2 marks]

Solution:

Concept:

- In normal adjustment, a refracting telescope forms its final image at infinity; the objective's rear focal plane coincides with the eyepiece's front focal plane.
- The lens separation is $L = f_o + f_e$, and the magnitude of the angular magnifying power is $|M| = f_o/f_e$, where f_o and f_e are the objective and eyepiece focal lengths.

Step 1: Form the two focal-length equations The supplied magnifying power is its magnitude. Using the separation in centimetres, 1.00 m = 100 cm, the two conditions give

$$f_o + f_e = 100 \text{ cm}, \quad \frac{f_o}{f_e} = 19.$$

Thus the objective must have nineteen times the focal length of the eyepiece. The image inversion would introduce a minus sign in the signed angular magnification, not in these positive focal lengths.

Step 2: Solve the simultaneous equations Substitute $f_o = 19f_e$ into the separation equation:

$$\begin{aligned} 19f_e + f_e &= 100 \text{ cm}, \\ f_e &= \frac{100}{20} \text{ cm} = 5 \text{ cm}, \\ f_o &= 19 \times 5 \text{ cm} = 95 \text{ cm}. \end{aligned}$$

Their sum is 100 cm and their ratio is 19, so both given conditions are satisfied.

Step 3: Conclusion The objective focal length is $f_o = 95 \text{ cm} = 0.95 \text{ m}$, and the eyepiece focal length is $f_e = 5 \text{ cm} = 0.05 \text{ m}$.

Quick Tip to Solve: In normal adjustment, use $f_e = L/(|M| + 1)$ first, then obtain $f_o = L - f_e$.

18. What are matter waves? A proton, an electron and an α -particle have the same kinetic energy. Write the de Broglie wavelengths associated with them in increasing order. [2 marks]

Solution:

Concept:

- Matter waves are the de Broglie waves associated with moving material particles. Their wavelength is $\lambda = h/p$, where h is Planck's constant and p is the particle's momentum.
- For a non-relativistic particle of mass m and kinetic energy K , $K = p^2/(2m)$; hence $\lambda = h/\sqrt{2mK}$.

Step 1: Describe the waves associated with matter A moving particle displays wave behaviour such as diffraction and interference. The waves expressing this behaviour are called matter waves or de Broglie waves. They are associated with material particles, including charged particles here; they are not electromagnetic radiation emitted merely because a particle moves.

Step 2: Compare wavelengths at equal kinetic energy The three particles have the same K , and h is

constant, so

$$\lambda \propto \frac{1}{\sqrt{m}}.$$

Their masses satisfy $m_\alpha > m_p > m_e$, with $m_\alpha \simeq 4m_p$. Therefore the alpha-particle has the greatest momentum at the given energy and the shortest wavelength, whereas the electron has the smallest momentum and the longest wavelength. In particular, $\lambda_\alpha \simeq \lambda_p/2$. Charge does not enter this equal-kinetic-energy comparison.

Step 3: Conclusion Matter waves are the de Broglie waves associated with moving material particles. The wavelengths in increasing order are $\lambda_\alpha < \lambda_p < \lambda_e$.

Quick Tip to Solve: Equal kinetic energy means $\lambda \propto 1/\sqrt{m}$: reverse the mass order to obtain the wavelength order.

19. A ray of light is incident normally on one face of an equilateral glass prism of refractive index μ . When the prism is completely immersed in a transparent medium, it is observed that the emergent ray just grazes the adjacent face. Find the refractive index of the medium. [2 marks]

Solution:

Concept:

- At normal incidence the ray enters undeviated, since Snell's law gives a zero angle of refraction.
- For a prism, the internal angles with the normals satisfy $r_1 + r_2 = A$, where A is the prism angle. At grazing emergence, the external refraction angle is 90° .

Step 1: Find the incidence angle at the second face The prism is equilateral, so $A = 60^\circ$. The ray is normal to the first face and hence $r_1 = 0^\circ$. Its incidence angle at the adjacent face is therefore

$$r_2 = A - r_1 = 60^\circ.$$

These angles are measured from the normals to the faces, not from the faces themselves.

Step 2: Apply Snell's law at grazing emergence Let the absolute refractive index of the surrounding medium be n_m . At the second boundary the light travels from glass, of index μ , into this medium. The emergent ray grazes the face, so its angle with the normal is 90° . Thus

$$\mu \sin 60^\circ = n_m \sin 90^\circ.$$

The second-face incidence angle is the critical angle for this glass-medium pair, consistent with the surrounding medium having a smaller index than the glass.

Step 3: Conclusion The refractive index of the surrounding transparent medium is

$$n_m = \frac{\sqrt{3}}{2} \mu.$$

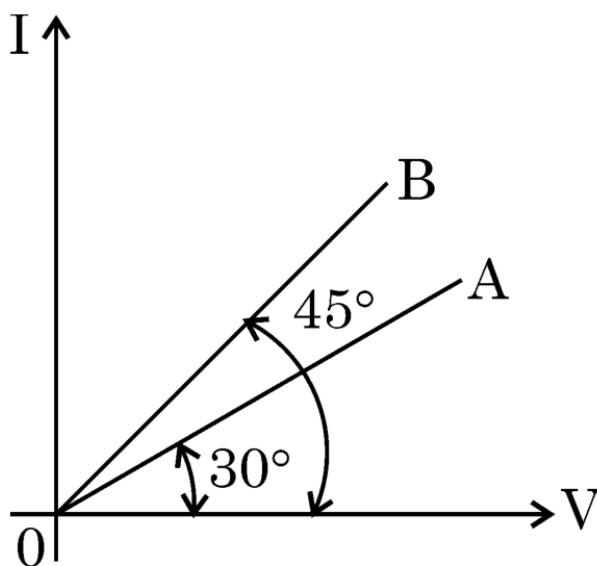
Quick Tip to Solve: Normal entry makes the incidence angle at the second face equal to the prism angle; grazing exit means the final angle with the normal is 90° .

20. Two wires A and B of different metals have their lengths in ratio $1 : 2$ and their radii in ratio $2 : 1$ respectively. I - V graphs for them is shown in the figure. Find the ratio of their

(i) Resistances (R_A/R_B) and

(ii) Resistivities (σ_A/σ_B)

[2 marks]



Solution:

Concept:

- In an I -versus- V graph the slope is conductance: $I/V = 1/R = \tan \theta$, where θ is measured from the positive voltage axis.
- A uniform wire has resistance $R = \rho L/(\pi r^2)$, where ρ , L and r are its resistivity, length and radius.

Step 1: Obtain the resistance ratio from the slopes The graph shows $\theta_A = 30^\circ$ and $\theta_B = 45^\circ$, both measured from the voltage axis. Since current is on the vertical axis, resistance is the reciprocal of the slope. Therefore

$$\frac{R_A}{R_B} = \frac{\tan 45^\circ}{\tan 30^\circ} = \frac{1}{1/\sqrt{3}} = \sqrt{3}.$$

The steeper line for wire B accordingly represents the smaller resistance, which checks the direction of this ratio.

Step 2: Include the length and cross-sectional area ratios The printed question uses σ for resistivity; denote this quantity conventionally by ρ , so $\sigma_A/\sigma_B = \rho_A/\rho_B$ here. Resistivity is $\rho = R\pi r^2/L$. Given $L_A/L_B = 1/2$ and $r_A/r_B = 2$, the cross-sectional area ratio is 4, not 2. Hence

$$\frac{\rho_A}{\rho_B} = \frac{R_A}{R_B} \left(\frac{r_A}{r_B} \right)^2 \frac{L_B}{L_A} = \sqrt{3} \times 4 \times 2 = 8\sqrt{3}.$$

The inverse length ratio appears because the resistivity is found by dividing resistance times area by the wire's length.

Step 3: Conclusion (i) $R_A : R_B = \sqrt{3} : 1$. (ii) $\sigma_A : \sigma_B = 8\sqrt{3} : 1$, with σ denoting the printed resistivity.

Quick Tip to Solve: Check which quantity is vertical before using a graph's slope, and square the given radius ratio when converting resistance to resistivity.

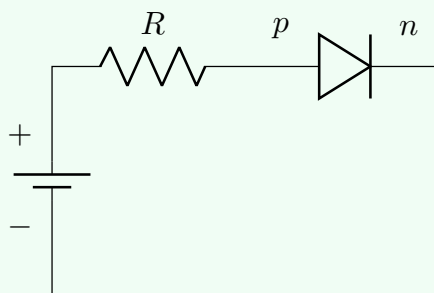
21. Draw the circuit diagram of a p - n junction diode in (i) forward biasing and (ii) reverse biasing. Also draw its I - V characteristics in the two cases. [2 marks]

Solution:

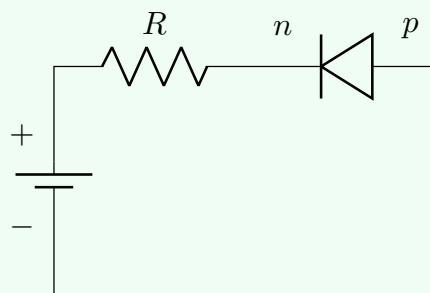
Concept:

- Forward bias connects the p -side (anode) to the positive terminal and the n -side (cathode) to the negative terminal of a battery. It reduces the junction barrier and depletion width.
- Reverse bias connects the n -side to positive and the p -side to negative. It increases the barrier and depletion width; the small reverse current is carried mainly by minority carriers.

Step 1: Draw the two biasing circuits The battery's positive terminal reaches p in forward bias and n in reverse bias; the other side returns to negative. The diode symbol's bar identifies n . A series resistor R limits current.



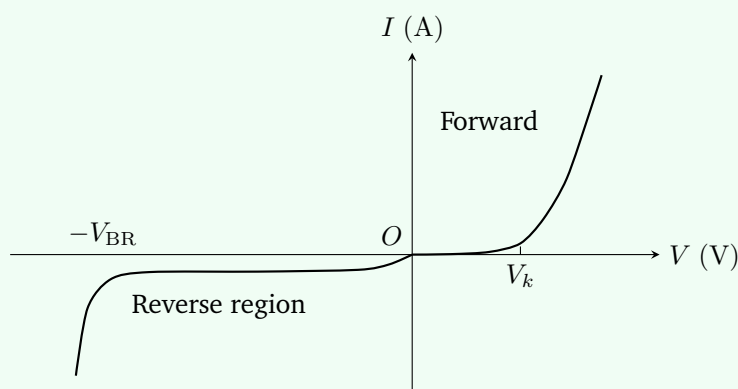
Forward bias



Reverse bias

Biasing circuits; the series resistor limits current.

Step 2: Draw and interpret the current-voltage characteristic Take $V = V_p - V_n$ and positive current in the forward direction. For forward bias $V > 0$, the current is initially small and rises rapidly beyond the knee voltage V_k . For reverse bias $V < 0$, a very small, nearly constant reverse saturation current flows until breakdown. At $V = -V_{BR}$, the reverse current increases sharply in magnitude. The graph is schematic: the small reverse current is enlarged for visibility, and the knee voltage depends on the semiconductor material.



Diode characteristic; reverse current is magnified and axes are schematic.

Step 3: Conclusion The circuits show the required opposite polarities. Forward current rises rapidly beyond the knee; reverse current remains very small until breakdown.

Quick Tip to Solve: Identify the diode's bar as the n -side first. Positive connected to the other, p -side means forward bias; keep reverse current below the current axis.

Section C (21 marks)

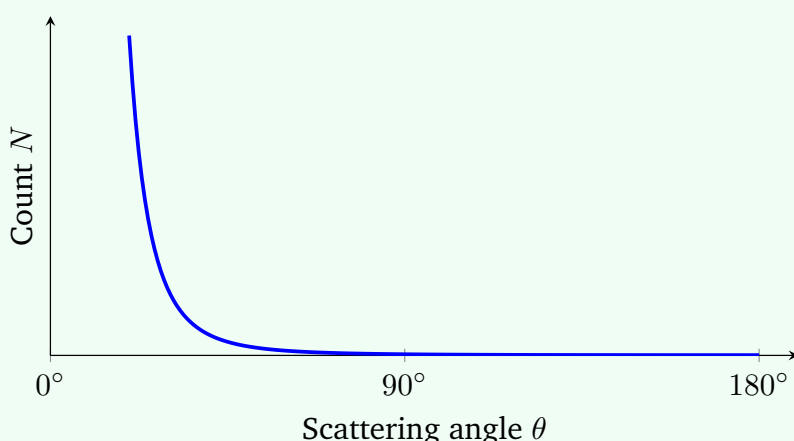
22. Draw the graph showing variation of scattered particles detected (N) with the scattering angle (θ) in Geiger-Marsden experiment. Write two conclusions that you can draw from this graph. Obtain the expression for the distance of closest approach in this experiment. [3 marks]

Solution:

Concept:

- In Rutherford scattering, the number N of scattered alpha particles detected in a fixed small solid angle varies as $N \propto 1/\sin^4(\theta/2)$, where θ is the scattering angle.
- For a head-on encounter with a heavy nucleus of charge $+Ze$, conservation of energy converts the initial alpha-particle kinetic energy K into electrostatic potential energy at the turning point. The alpha particle has charge $+2e$.

Step 1: Sketch the angular distribution The count is very large at small scattering angles and decreases sharply as θ increases. Only a very small count remains near 180° . The graph shows the qualitative distribution; the forward direction $\theta = 0$ is not assigned a finite Rutherford-law value.



Scattered-particle count versus scattering angle (schematic; arbitrary vertical scale).

Step 2: Infer the atomic structure First, the overwhelming predominance of undeflected or slightly deflected particles indicates that most of the atom is empty space. Second, the very small fraction scattered through large angles, including nearly backward scattering, shows that the positive charge and almost all the atomic mass are concentrated in a very small, dense nucleus. A diffuse positive charge could not provide the strong repulsion needed for these rare large deflections.

Step 3: Apply energy conservation to a head-on particle Let the alpha particle approach from far away with speed v and mass m_α , so $K = \frac{1}{2}m_\alpha v^2$, taking the initial potential energy as zero. For a head-on collision its instantaneous speed becomes zero at the distance of closest approach r_0 . Neglecting recoil of the heavy nucleus,

$$K = \frac{1}{4\pi\epsilon_0} \frac{(2e)(Ze)}{r_0}.$$

Rearranging gives

$$r_0 = \frac{1}{4\pi\epsilon_0} \frac{2Ze^2}{K} = \frac{1}{4\pi\epsilon_0} \frac{4Ze^2}{m_\alpha v^2}.$$

Step 4: Conclusion The count falls rapidly with scattering angle, supporting an atom that is mostly empty space with a tiny, massive, positively charged nucleus. The head-on distance of closest approach

is $r_0 = \frac{2Ze^2}{4\pi\epsilon_0 K}$, where K is the incident alpha-particle kinetic energy.

Quick Tip to Solve: At closest approach use the product of charges $(2e)(Ze)$, and set kinetic energy to zero only for the head-on turning point.

23. A thin spherical conducting shell of radius R has a charge q . A point charge Q is placed at the centre of the shell. Find

(i) The charge density on the outer surface of the shell, and

(ii) the potential at a distance of $(R/2)$ from the centre of the shell.

[3 marks]

Solution:

Concept:

- The electric field inside conducting material is zero in electrostatic equilibrium. Gauss's law therefore requires the total charge enclosed by a Gaussian surface within the metal to vanish.
- Potentials add algebraically. A spherical shell of radius R carrying charge q_s contributes the constant potential kq_s/R at all interior points, where $k = 1/(4\pi\epsilon_0)$ and the reference is zero potential at infinity.

Step 1: Determine the induced surface charges Denote the inner and outer surface charges by q_{in} and q_{out} . A Gaussian surface inside the conducting material encloses the central charge and the inner surface charge. Hence

$$Q + q_{\text{in}} = 0, \quad q_{\text{in}} = -Q.$$

The shell itself still has total charge q , so charge conservation gives

$$q_{\text{out}} = q - q_{\text{in}} = q + Q.$$

The charge is at the centre, preserving spherical symmetry; consequently each surface distribution is uniform.

Step 2: Calculate the outer surface charge density The outer area of the thin spherical shell is $4\pi R^2$. Dividing the outer surface charge by this area gives the answer to part (i):

$$\sigma_{\text{out}} = \frac{q + Q}{4\pi R^2}.$$

This is a signed density; it is not generally $q/(4\pi R^2)$, because the central charge redistributes the shell's charge.

Step 3: Superpose the potentials at half the radius At $r = R/2$, the point charge contributes $kQ/(R/2) = 2kQ/R$. In the thin-shell limit, both shell surfaces have radius R ; their combined potential in the cavity is

$$V_{\text{shell}} = k\frac{-Q}{R} + k\frac{q + Q}{R} = k\frac{q}{R}.$$

Therefore, the answer to part (ii), relative to infinity, is

$$V(R/2) = \frac{2kQ}{R} + \frac{kq}{R} = \frac{q + 2Q}{4\pi\epsilon_0 R}.$$

The cavity potential need not be constant because the central point charge creates an electric field

there; only the conducting material is an equipotential.

Step 4: Conclusion (i) $\sigma_{\text{out}} = \frac{q + Q}{4\pi R^2}$.

(ii) $V(R/2) = \frac{q + 2Q}{4\pi\epsilon_0 R}$, taking $V(\infty) = 0$.

Quick Tip to Solve: First put $-Q$ on the inner surface, then conserve the shell's net charge. Inside a thin shell use kq/R , while the point charge contributes kQ/r .

24. (a) Differentiate between nuclear fission and fusion.

(b) The fission properties of ${}^{239}_{94}\text{Pu}$ are very similar to those of ${}^{235}_{92}\text{U}$. How much energy (in MeV), is released if all the atoms in 1 g of pure ${}^{239}_{94}\text{Pu}$ undergo fission? The average energy released per fission is 180 MeV. [3 marks]

Solution:

Concept:

- Nuclear fission splits a heavy nucleus into lighter nuclei, usually with emission of neutrons. Nuclear fusion combines light nuclei into a heavier nucleus.
- Energy is released when the products have greater total binding energy than the reactants. For a sample of mass m and molar mass M , the number of nuclei is $N = (m/M)N_A$, with $N_A = 6.022 \times 10^{23} \text{ mol}^{-1}$.

Step 1: Distinguish fission from fusion In part (a), fission is the division of a heavy nucleus, such as uranium or plutonium, into two intermediate-mass fragments, generally releasing neutrons. Those neutrons can cause further fissions, allowing a chain reaction. Fusion is the joining of light nuclei, such as hydrogen isotopes, to form a heavier nucleus. It requires extremely high temperature and suitable density or confinement to overcome the electrostatic repulsion between the approaching nuclei. Both processes can release energy, but one splits heavy nuclei whereas the other combines light nuclei.

Step 2: Count the plutonium nuclei in the sample For part (b), each atom of pure ${}^{239}_{94}\text{Pu}$ contains one plutonium nucleus. Use its molar mass $M \simeq 239 \text{ g mol}^{-1}$ and the given mass $m = 1 \text{ g}$:

$$N = \frac{1 \text{ g}}{239 \text{ g mol}^{-1}} (6.022 \times 10^{23} \text{ mol}^{-1}) = 2.5197 \times 10^{21}.$$

The mass number 239, not the atomic number 94, determines the approximate molar mass used here.

Step 3: Multiply by the energy released per fission All the nuclei undergo fission, and the average energy per event is 180 MeV. Hence the total energy is

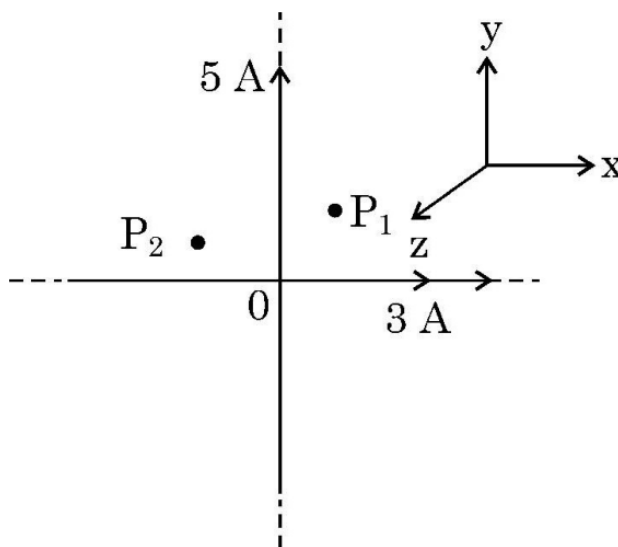
$$\begin{aligned} E &= N \times 180 \text{ MeV} \\ &= (2.5197 \times 10^{21})(180) \text{ MeV} \\ &= 4.5354 \times 10^{23} \text{ MeV}. \end{aligned}$$

No conversion into joules is needed because the question explicitly requests the result in MeV. The given energy already accounts for the average energy release in each fission event.

Step 4: Conclusion Fission splits a heavy nucleus; fusion combines light nuclei. Complete fission of 1 g of pure ${}^{239}_{94}\text{Pu}$ releases approximately $4.54 \times 10^{23} \text{ MeV}$.

Quick Tip to Solve: For energy from a mass of nuclear fuel, use $E = (m/M)N_A E_f$. Keep m and M in matching mass units and retain MeV when it is requested.

25. Two long insulated straight wires carrying currents of 3 A and 5 A are arranged in XY plane as shown in figure. Find the magnitude and direction of the net magnetic fields at points $P_1(2 \text{ m}, 2 \text{ m})$ and $P_2(-1 \text{ m}, 1 \text{ m})$. [3 marks]



Solution:

Concept:

- A long straight wire carrying current I produces a magnetic field $B = \mu_0 I / (2\pi r)$, where r is the perpendicular distance from the wire and $\mu_0 / (2\pi) = 2 \times 10^{-7} \text{ T m A}^{-1}$.
- Use the right-hand thumb rule for each wire, then add the fields as vectors. Here the currents flow along $+x$ and $+y$, and both fields at points in the XY plane lie along the z -axis.

Step 1: Assign the distances and directions The horizontal wire carries 3 A along $+x$; its perpendicular distance from (x, y) is $|y|$. The vertical wire carries 5 A along $+y$; its distance is $|x|$. Both points have $y > 0$, so the horizontal wire produces a field along $+z$. The vertical wire gives a field along $-z$ for $x > 0$, and along $+z$ for $x < 0$.

Step 2: Superpose the fields at the first point At $P_1(2 \text{ m}, 2 \text{ m})$, both perpendicular distances are 2 m. Taking $\hat{z}$ along the positive z -axis,

$$\begin{aligned} \mathbf{B}_{3\text{A}} &= 2 \times 10^{-7} \frac{3}{2} \hat{z} = 3 \times 10^{-7} \hat{z} \text{ T}, \\ \mathbf{B}_{5\text{A}} &= -2 \times 10^{-7} \frac{5}{2} \hat{z} = -5 \times 10^{-7} \hat{z} \text{ T}, \\ \mathbf{B}(P_1) &= (3 - 5) \times 10^{-7} \hat{z} \text{ T}. \end{aligned}$$

The contributions oppose; the stronger field is that of the vertical wire.

Step 3: Superpose the fields at the second point At $P_2(-1 \text{ m}, 1 \text{ m})$, the distance from each wire is 1 m. Here both contributions point along $+z$, so their magnitudes add:

$$\mathbf{B}(P_2) = 2 \times 10^{-7} \left(\frac{3}{1} + \frac{5}{1} \right) \hat{\mathbf{z}} = 1.6 \times 10^{-6} \hat{\mathbf{z}} \text{ T}.$$

Step 4: Conclusion At P_1 , the net field is $2.0 \times 10^{-7} \text{ T}$ along $-z$ (into the XY plane). At P_2 , it is $1.6 \times 10^{-6} \text{ T}$ along $+z$ (out of the XY plane).

Quick Tip to Solve: Use $|y|$ for the distance from the horizontal wire and $|x|$ for the vertical wire. Decide each field's direction before adding magnitudes.

26. What is meant by displacement current? How is this current different from the conduction current? A capacitor is being charged by a source of emf. Justify the continuity of current in the circuit. [3 marks]

Solution:

Concept:

- Displacement current is the current associated with a time-varying electric field. In vacuum, $I_d = \epsilon_0 d\Phi_E/dt$, where $\Phi_E = \int \mathbf{E} \cdot d\mathbf{A}$ is the electric flux through a surface.
- The Ampere–Maxwell law includes both conduction and displacement currents: $\oint \mathbf{B} \cdot d\boldsymbol{\ell} = \mu_0(I_c + I_d)$. This gives a consistent magnetic field for any spanning surface of the same loop.

Step 1: Explain displacement current and compare it with conduction current A changing electric flux produces a magnetic field just as a conduction current does. The quantity $\epsilon_0 d\Phi_E/dt$, with the dimensions of current, is called displacement current. It can exist in vacuum or in the insulating space between capacitor plates, without free charges crossing that space. Conduction current, by contrast, results from the actual transport of free charges through a conductor, such as the drift of electrons in a connecting wire. A steady electric field can maintain conduction current in a resistive wire, whereas displacement current requires the electric field to change with time.

Step 2: Relate the changing field to the charge on a capacitor Consider an ideal parallel-plate capacitor with plate area A , neglecting edge effects and taking the gap to be vacuum or air. At an instant when the magnitude of charge on each plate is Q , the approximately uniform field and its flux through the gap are

$$E = \frac{Q}{\epsilon_0 A}, \quad \Phi_E = EA = \frac{Q}{\epsilon_0}.$$

Charge supplied by the source accumulates on the plates, so the conduction current in the wires is $I_c = dQ/dt$.

Step 3: Establish continuity during charging Differentiating the electric flux between the plates gives

$$I_d = \epsilon_0 \frac{d\Phi_E}{dt} = \epsilon_0 \frac{d}{dt} \left(\frac{Q}{\epsilon_0} \right) = \frac{dQ}{dt} = I_c.$$

Thus the current in a wire is continued through the capacitor gap as displacement current of equal magnitude. A surface cutting a wire intercepts conduction current; a surface bulging between the plates intercepts displacement current instead. Including both terms makes the Ampere–Maxwell law

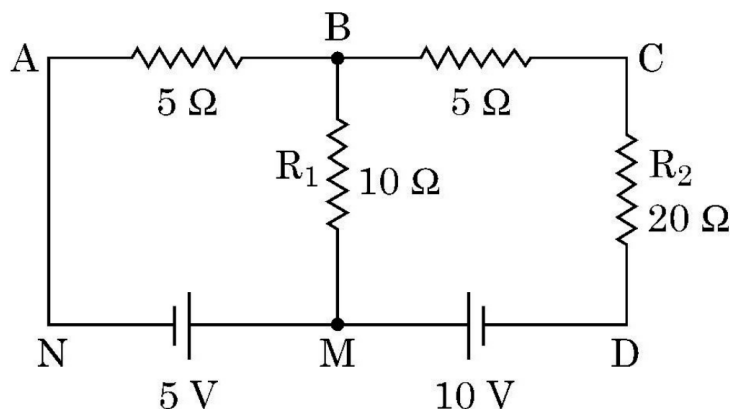
consistent, although no conduction charge passes across the ideal insulating gap.

Step 4: Conclusion Displacement current is due to changing electric flux, while conduction current is due to free-charge transport. For a charging capacitor, $I_d = I_c = dQ/dt$, ensuring continuity of the total current throughout the circuit.

Quick Tip to Solve: For a charging capacitor, first write $EA = Q/\epsilon_0$; differentiating immediately gives $\epsilon_0 d(EA)/dt = dQ/dt$.

27. Find the currents flowing through the branches AB and BC in the network shown.

[3 marks]



Solution:

Concept:

- Kirchhoff's junction rule follows from charge conservation: the algebraic sum of currents leaving a junction is zero.
- For a resistor between nodes at potentials V_1 and V_2 , the current from node 1 to node 2 is $I = (V_1 - V_2)/R$. The longer line of a cell symbol denotes its positive terminal.

Step 1: Read the battery polarities and choose a reference Both batteries have their positive terminals connected to M . Choose $V_M = 0$. The ideal wires connect A to N , so the printed polarities give

$$V_A = V_N = -5\text{V}, \quad V_D = -10\text{V}.$$

The 5Ω resistor from B to C and the 20Ω resistor from C to D are in series, because no other branch leaves C . Their combined resistance is 25Ω .

Step 2: Apply the junction rule at B Let $V_B = V$, in volts. Write each current as leaving B , through the left, central and right paths respectively:

$$\frac{V - (-5)}{5} + \frac{V - 0}{10} + \frac{V - (-10)}{25} = 0.$$

Multiplying by 50 and collecting terms gives

$$10(V + 5) + 5V + 2(V + 10) = 0, \quad 17V + 70 = 0.$$

Hence $V_B = -70/17\text{V}$. A negative current in an assumed outgoing branch simply means that its actual direction is towards the junction.

Step 3: Calculate the requested branch currents Since $V_B > V_A$, the current in the left resistor flows

from B to A :

$$I_{B \rightarrow A} = \frac{V_B - V_A}{5} = \frac{-70/17 + 5}{5} = \frac{3}{17} \text{ A.}$$

The current through BC equals that through the complete series path BCD :

$$I_{B \rightarrow C} = \frac{V_B - V_D}{25} = \frac{-70/17 + 10}{25} = \frac{4}{17} \text{ A.}$$

As a consistency check, the central branch supplies $(0 - V_B)/10 = 7/17 \text{ A}$ from M to B , equal to the sum $3/17 + 4/17$ leaving B .

Step 4: Conclusion The current in branch AB is $3/17 \text{ A} \approx 0.176 \text{ A}$, from B to A . The current in branch BC is $4/17 \text{ A} \approx 0.235 \text{ A}$, from B to C .

Quick Tip to Solve: Take the common positive battery junction M as zero potential. Combine the resistors along BCD , then one junction equation at B determines both requested currents.

28(a)(i). Define mutual inductance. Write its SI unit.

[3 marks total]

Solution:

Concept:

- Mutual induction is the production of an emf in one coil when the current in a neighbouring coil changes, because its linked magnetic flux changes.
- If current I_1 in coil 1 produces flux Φ_{21} through each of the N_2 turns of coil 2, their mutual inductance is $M = N_2 \Phi_{21} / I_1$, for fixed geometry and a linear medium.

Step 1: Define the coefficient of mutual induction The mutual inductance of two coils is the magnetic flux linkage with either coil per unit current flowing in the other coil. Equivalently, it is the magnitude of emf induced in one coil when the current in the other changes at unit rate. Faraday's law gives

$$\varepsilon_2 = -M \frac{dI_1}{dt}.$$

The minus sign expresses Lenz's law: the induced emf opposes the change in linked flux.

Step 2: Identify its SI unit From the emf relation, the unit of mutual inductance is volt second per ampere, called the henry:

$$1 \text{ H} = 1 \text{ V s A}^{-1} = 1 \text{ Wb A}^{-1}.$$

Two coils have mutual inductance one henry if a current change of 1 A s^{-1} in one induces an emf of magnitude 1 V in the other.

Step 3: Conclusion Mutual inductance is flux linkage in one coil per unit current in the other, $M = N_2 \Phi_{21} / I_1$. Its SI unit is the **henry (H)**.

Quick Tip to Solve: Use total flux linkage $N\Phi$, not the flux through just one turn, when defining mutual inductance.

28(a)(ii). Derive an expression for the mutual inductance of a system of two long coaxial solenoids of same length l , having turns N_1 and N_2 and of radii r_1 and r_2 ($r_2 > r_1$).

Solution:

Concept:

- A long air-core solenoid of length l , N turns and current I produces an approximately uniform internal field $B = \mu_0 NI/l$; its external field is negligible.
- Mutual inductance is the flux linkage in the receiving solenoid per unit current in the source: $M = N_2 \Phi_{21}/I_1$. The permeability of free space is μ_0 .

Step 1: Find the magnetic field of the inner solenoid Let current I_1 flow in the inner solenoid of radius r_1 , length l and N_1 turns. Neglecting end effects for the two long coaxial solenoids, its internal magnetic field is

$$B_1 = \mu_0 \frac{N_1}{l} I_1.$$

The field is confined approximately to the cross-sectional area $A_1 = \pi r_1^2$.

Step 2: Calculate the flux linkage with the outer solenoid Every turn of the outer solenoid encloses the inner solenoid. Since $r_2 > r_1$, only the area πr_1^2 within an outer turn contains the field B_1 ; the additional annular area contributes negligible flux. Hence

$$\Phi_{21} = B_1 \pi r_1^2, \quad N_2 \Phi_{21} = \frac{\mu_0 N_1 N_2 \pi r_1^2}{l} I_1.$$

Dividing this linkage by I_1 gives the mutual inductance. Reversing the source and receiving coils gives the same result: the outer solenoid's field links the area of each inner turn.

Step 3: Conclusion For the two long coaxial solenoids in air,

$$M = \frac{\mu_0 N_1 N_2 \pi r_1^2}{l}.$$

The smaller radius determines the common linked area; M is measured in henries. If both solenoids have a uniform magnetic core of permeability μ , replace μ_0 by μ .

Quick Tip to Solve: In coaxial solenoid problems, use the smaller cross-sectional area for the common flux, even when the receiving solenoid is larger.

OR

28(b). What are ferromagnetic materials? Explain ferromagnetism with the help of suitable diagrams, using the concept of magnetic domain. [3 marks]

Solution:

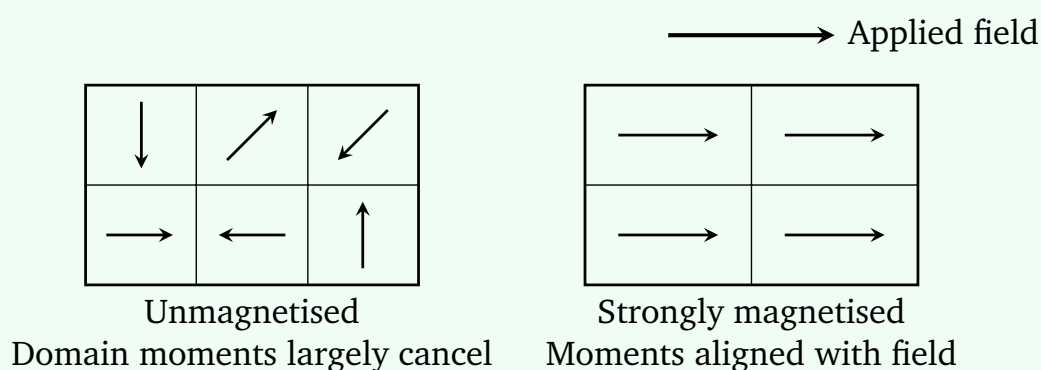
Concept:

- Ferromagnetic substances, such as iron, cobalt and nickel, are strongly attracted by a magnetic field and can acquire a large magnetisation in the direction of the applied field.
- A magnetic domain is a small region in which the atomic magnetic moments are spontaneously aligned parallel, giving that region a large resultant magnetic moment.
- The magnetisation of a specimen depends on the vector sum of the moments of its many domains,

not just on the alignment within one domain.

Step 1: Describe the unmagnetised specimen Even without an external field, the atomic moments within each domain are aligned. However, in an unmagnetised piece, different domains point in different directions. Their magnetic moments largely cancel, so the specimen has approximately zero resultant magnetisation. The first sketch represents domain boundaries and the direction of the resultant moment in each domain; each arrow stands for many parallel atomic moments.

Step 2: Apply an external magnetic field When a field is applied, domains whose moments are favourably oriented along it grow at the expense of less favourably oriented domains through domain-wall motion. The moments can also rotate towards the field direction. Thus the domain moments no longer cancel: a large net magnetic moment develops along the field. At a sufficiently strong field almost all moments become aligned and the specimen approaches magnetic saturation, as represented by the second sketch. Some alignment can remain after the field is removed, explaining remanent magnetisation and the formation of permanent magnets.



Schematic domains before magnetisation and near saturation. Arrows show domain magnetic moments.

Step 3: Conclusion Ferromagnetism arises from parallel atomic moments within domains and the growth and alignment of those domains in an applied magnetic field, producing strong magnetisation.

Quick Tip to Solve: In domain sketches, show different directions before magnetisation and arrows along the applied field afterwards; do not show random atomic moments inside a single domain.

Section D (8 marks)

Note : Questions number 29 to 30 are Case Study based questions. Read the following paragraph and answer the questions that follow.

29. A lens is a transparent optical medium bounded by two surfaces; at least one of which should be spherical. Applying the formula of image formation by a single spherical surface successively at the two surfaces of a thin lens, a formula known as lens maker's formula and hence the basic lens formula can be obtained. The focal length (or power) of a lens depends on the radii of its surfaces and the refractive index of its material with respect to the surrounding medium. The refractive index of a material depends on the wavelength of light used. Combination of lenses helps us to obtain diverging or converging lenses of desired power and magnification. [4 marks]

29(i). A thin converging lens of focal length 20 cm and a thin diverging lens of focal length 15 cm are placed coaxially in contact. The power of the combination is [1 mark]

- (A) $-\frac{5}{6}$ D
(B) $-\frac{5}{3}$ D
(C) $\frac{4}{3}$ D
(D) $\frac{3}{2}$ D

Correct Answer: (B) $-\frac{5}{3}$ D

Solution:

Concept:

- The power of a thin lens is $P = 1/f$, with focal length f in metres and power in dioptries (D).
- Powers add for thin lenses in contact: $P = P_1 + P_2$. A converging lens has positive focal length and a diverging lens has negative focal length.

Step 1: Assign signed focal lengths The converging lens has $f_1 = +0.20$ m, while the diverging lens has $f_2 = -0.15$ m. Thus their powers are $+5$ D and $-20/3$ D, respectively. The negative sign of the second power is essential.

Step 2: Add the two powers

$$P = 5 - \frac{20}{3} = \frac{15 - 20}{3} = -\frac{5}{3} \text{ D.}$$

The diverging lens has the greater power magnitude, so the net power must be negative. This rules out (C) and (D); option (A), $-5/6$ D, is not the algebraic sum. Focal lengths themselves must not be added.

Step 3: Conclusion The power is $-\frac{5}{3}$ D, so the combination is diverging. Hence, the correct option is (B).

Quick Tip to Solve: Convert centimetres to metres and assign the concave lens a negative focal length before adding reciprocal focal lengths.

29(ii). The radii of curvature of two surfaces of a convex lens are R and $2R$. If the focal length of this lens is $\left(\frac{4}{3}\right) R$, the refractive index of the material of the lens is: [1 mark]

- (A) $\frac{5}{3}$
- (B) $\frac{4}{3}$
- (C) $\frac{3}{2}$
- (D) $\frac{7}{5}$

Correct Answer: (C) $\frac{3}{2}$

Solution:

Concept:

- For a thin lens in air, lens maker's formula is $1/f = (n - 1)(1/R_1 - 1/R_2)$, where n is its refractive index and the radii carry Cartesian signs.
- For light travelling left to right through a biconvex lens, the first radius is positive and the second is negative.

Step 1: Apply the radius signs Take $R_1 = +R$ and $R_2 = -2R$. The curvature factor is therefore

$$\frac{1}{R_1} - \frac{1}{R_2} = \frac{1}{R} + \frac{1}{2R} = \frac{3}{2R}.$$

Reversing the lens gives the same sum of curvature magnitudes and hence the same power.

Step 2: Substitute the printed focal length The official question gives $f = 4R/3$, so

$$\begin{aligned} \frac{3}{4R} &= (n - 1) \frac{3}{2R}, \\ n - 1 &= \frac{1}{2}, \quad n = \frac{3}{2}. \end{aligned}$$

As a check, the indices in (A), (B) and (D) would give focal lengths R , $2R$ and $5R/3$, respectively, which do not equal the specified $4R/3$.

Step 3: Conclusion The refractive index is $n = \frac{3}{2} = 1.5$. Hence, the correct option is (C).

Quick Tip to Solve: Opposite signs of the two radii make their reciprocal magnitudes add for a biconvex lens; cancel the common radius before solving for the index.

29(iii). The focal length of an equiconvex lens

[1 mark]

- (A) increases when the lens is dipped in water.
- (B) increases when the wavelength of incident light decreases.
- (C) increases with decrease in radius of curvature of its surface.
- (D) decreases when the lens is cut into two identical parts along its principal axis.

Correct Answer: (A) increases when the lens is dipped in water.

Solution:

Concept:

- For an equiconvex thin lens of radius magnitude R in a medium, $1/f = 2(n_{\text{rel}} - 1)/R$, where $n_{\text{rel}} = n_{\text{lens}}/n_{\text{medium}}$.
- Focal length depends on relative refractive index and surface curvature; changing aperture alone does not change the paraxial focal length.

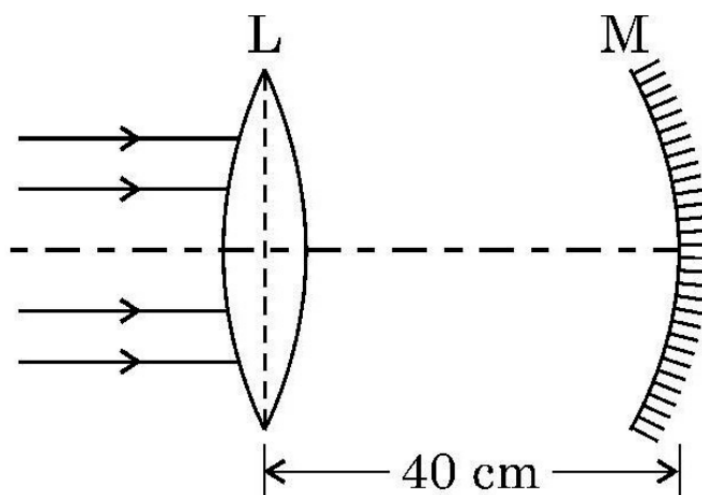
Step 1: Compare air and water Immersing an ordinary glass lens in water increases the refractive index of the surrounding medium. The relative index and hence $n_{\text{rel}} - 1$ decrease while the curvature remains fixed. The lens therefore has smaller positive power and a longer focal length, as stated in (A).

Step 2: Check the other proposed changes Under normal dispersion, decreasing the wavelength increases the refractive index of glass, increasing power and decreasing focal length; (B) is false. At fixed refractive index, $f = R/[2(n_{\text{rel}} - 1)]$, so decreasing R decreases f ; (C) is false. Cutting along the principal axis reduces the aperture of each half but preserves the curved surfaces' radii and refractive index, so each half retains the original focal length; (D) is false.

Step 3: Conclusion The focal length increases when the lens is dipped in water. Hence, the correct option is (A).

Quick Tip to Solve: Separate curvature and refractive-index changes from aperture changes: cutting along the axis changes brightness, whereas immersion changes power.

29(iv)(a). A thin convex lens L of focal length 10 cm and a concave mirror M of focal length 15 cm are placed coaxially 40 cm apart as shown in figure. A beam of light coming parallel to the principal axis is incident on the lens. The final image will be formed at a distance of [1 mark]



- (A) 10 cm, left of lens
- (B) 10 cm, right of lens
- (C) 20 cm, left of lens
- (D) 20 cm, right of lens

Correct Answer: No option describes the full optical path: the final image is at infinity; (B) is the intermediate image before return through the lens.

Solution:

Concept:

- A parallel beam forms an image at the focus of a convex lens. For subsequent refraction, use $\frac{1}{v} - \frac{1}{u} = \frac{1}{f}$, with distances measured in the current direction of incident light.
- A concave mirror returns rays from its centre of curvature to that same point; its radius of curvature is $R = 2f$.

Step 1: Locate the first image The incident parallel beam is focused 10 cm to the right of the lens. This point is $40 - 10 = 30$ cm in front of the mirror. Since the mirror has focal length 15 cm, that point is its centre of curvature.

Step 2: Follow reflection at the mirror The mirror re-forms an image at the same point, 30 cm in front of itself, or 10 cm to the right of the lens. This is the intermediate image corresponding to option (B). Options (A), (C) and (D) do not describe even this mirror image.

Step 3: Include the return passage through the lens The reflected light crosses that intermediate image and continues leftwards through the lens. The object for this return passage is at the right-hand focus of the lens, so $u = -10$ cm, $f = +10$ cm, with leftwards now positive. Thus

$$\frac{1}{v} = \frac{1}{10} - \frac{1}{10} = 0.$$

The final emergent rays are parallel. The printed phrase the final image does not specify stopping at the mirror; for the complete optical path none of the finite-distance options is correct.

Step 4: Conclusion The complete lens–mirror–lens system produces a final image at infinity. No

printed option gives this result. Option (B), 10 cm right of the lens, describes the intermediate mirror image only.

Quick Tip to Solve: In a lens–mirror arrangement, trace the returning rays through the lens again before selecting a final-image option.

OR

29(iv)(b). A beam of light coming parallel to the principal axis of a convex lens L_1 of focal length 16 cm is incident on it. Another convex lens L_2 of focal length 12 cm is placed coaxially at a distance 40 cm from L_1 . The nature and distance of the final image from L_2 will be [1 mark]

- (A) real, 24 cm
- (B) virtual, 12 cm
- (C) real, 32 cm
- (D) virtual, 18 cm

Correct Answer: (A) real, 24 cm

Solution:

Concept:

- A convex lens focuses parallel incident rays at its principal focus.
- For the second thin lens, $1/v - 1/u = 1/f$; a real object on the incident side has $u < 0$, and a real image on the outgoing side has $v > 0$.

Step 1: Find the object for the second lens The first lens forms an image 16 cm to its right. Since the separation is 40 cm, this point is $40 - 16 = 24$ cm to the left of L_2 . Rays have crossed there and diverge on reaching L_2 , so it is a real object: $u_2 = -24$ cm.

Step 2: Apply the lens formula For $f_2 = +12$ cm,

$$\frac{1}{v_2} = \frac{1}{12} - \frac{1}{24} = \frac{1}{24} \text{ cm}^{-1}.$$

The positive image distance indicates convergence on the outgoing side. A virtual image is therefore excluded, eliminating (B) and (D); 32 cm in (C) does not satisfy the lens formula.

Step 3: Conclusion The final image is real and forms 24 cm to the right of L_2 . Hence, the correct option is (A).

Quick Tip to Solve: The intermediate image is at twice the second focal length from L_2 , so its image must also be at $2f_2$.

30. A pure semiconductor like Ge or Si, when doped with a small amount of suitable impurity, becomes an extrinsic semiconductor. In thermal equilibrium, the electron and hole concentration in it are related to the concentration of intrinsic charge carriers. A p-type or n-type semiconductor can be converted into a p-n junction by doping it with suitable impurity. Two processes, diffusion and drift take place during formation of a p-n junction. A semiconductor diode is basically a p-n junction with metallic contacts provided at the ends for the application of an external voltage. A p-n junction diode allows currents to pass only in one direction when it is forward biased. Due to this property, a diode is widely used to rectify alternating voltages, in half-wave or full wave configuration. [4 marks]

30(i). When Ge is doped with pentavalent impurity, the energy required to free the weakly bound electron from the dopant is about [1 mark]

- (A) 0.001 eV
- (B) 0.01 eV
- (C) 0.72 eV
- (D) 1.1 eV

Correct Answer: (B) 0.01 eV

Solution:

Concept:

- A pentavalent impurity acts as a donor in germanium: four valence electrons form covalent bonds and the fifth is weakly bound.
- The donor energy level lies just below the conduction band. Its ionisation energy is far smaller than the intrinsic band gap.

Step 1: Identify the electron being freed The question asks for the extra donor electron, not an electron promoted across the full valence-to-conduction band gap. Because this fifth electron is weakly bound to the dopant, a small thermal energy can release it into the conduction band.

Step 2: Compare the listed energies For pentavalent-doped Ge the characteristic donor ionisation energy is about 0.01 eV. The 0.001 eV value is an order of magnitude too small for this textbook estimate. The values 0.72 eV and 1.1 eV are of the scale of semiconductor band gaps, rather than the shallow donor binding energy.

Step 3: Conclusion The required energy is about 0.01 eV. Hence, the correct option is (B).

Quick Tip to Solve: For a dopant electron, look for the shallow donor energy, not the much larger intrinsic band gap.

30(ii). At a given temperature, the number of intrinsic charge carriers in a semiconductor is $2.0 \times 10^{10} \text{ cm}^{-3}$. It is doped with pentavalent impurity atoms. As a result, the number of holes in it becomes $8 \times 10^3 \text{ cm}^{-3}$. The number of electrons in the semiconductor is [1 mark]

- (A) $2 \times 10^{24} \text{ m}^{-3}$
- (B) $4 \times 10^{23} \text{ m}^{-3}$
- (C) $1 \times 10^{22} \text{ m}^{-3}$
- (D) $5 \times 10^{22} \text{ m}^{-3}$

Correct Answer: (D) $5 \times 10^{22} \text{ m}^{-3}$

Solution:

Concept:

- In thermal equilibrium the mass-action law is $n_e n_h = n_i^2$, where n_e , n_h and n_i are electron, hole and intrinsic carrier densities at the same temperature.
- A density in cm^{-3} is multiplied by 10^6 to express it in m^{-3} , since $1 \text{ m}^3 = 10^6 \text{ cm}^3$.

Step 1: Substitute the printed densities Use the printed values $n_i = 2.0 \times 10^{10} \text{ cm}^{-3}$ and $n_h = 8 \times 10^3 \text{ cm}^{-3}$. Thus

$$n_e = \frac{n_i^2}{n_h} = \frac{(2.0 \times 10^{10})^2}{8 \times 10^3} = 5 \times 10^{16} \text{ cm}^{-3}.$$

Pentavalent doping increases the electron density while reducing the hole density.

Step 2: Convert to the units of the options All options use m^{-3} , so

$$n_e = 5 \times 10^{16} \times 10^6 = 5 \times 10^{22} \text{ m}^{-3}.$$

The numerical values in (A), (B) and (C) do not equal this result; they arise from an incorrect coefficient, exponent or density conversion.

Step 3: Conclusion The electron density is $5 \times 10^{22} \text{ m}^{-3}$. Hence, the correct option is (D).

Quick Tip to Solve: Square the entire intrinsic density first, divide in consistent units, then multiply a per-cubic-centimetre result by 10^6 .

30(iii)(a). During the formation of a p - n junction — [1 mark]

- (A) electrons diffuse from p -region into n -region and holes diffuse from n -region into p -region.
- (B) both electrons and holes diffuse from n -region into p -region.
- (C) electrons diffuse from n -region into p -region and holes diffuse from p -region into n -region.
- (D) both electrons and holes diffuse from p -region into n -region.

Correct Answer: (C) electrons diffuse from n -region into p -region and holes diffuse from p -region into n -region.

Solution:

Concept:

- Diffusion is carrier motion from a region of higher carrier concentration to one of lower concentration.
- Electrons are the majority carriers in the n -region; holes are the majority carriers in the p -region.

Step 1: Track the electron concentration gradient Before equilibrium is established, the electron

concentration is much greater on the n -side. Electrons therefore diffuse across the junction from the n -region into the p -region. Options (A) and (D), which send electrons in the opposite direction, fail this condition.

Step 2: Track the hole concentration gradient Holes have the larger concentration on the p -side and diffuse into the n -region. Their diffusion direction is opposite to that of electrons, so (B), which sends both carriers from n to p , is also incorrect. These carrier motions must not be confused with conventional current direction or the opposite drift caused by the junction field.

Step 3: Conclusion Electrons diffuse from n to p , and holes diffuse from p to n . Hence, the correct option is (C).

Quick Tip to Solve: For diffusion, independently send each carrier from its majority-carrier side to its minority-carrier side.

OR

30(iii)(b). Initially during the formation of a p - n junction —

[1 mark]

- (A) diffusion current is large and drift current is small.
- (B) diffusion current is small and drift current is large.
- (C) both the diffusion and the drift currents are large.
- (D) both the diffusion and the drift currents are small.

Correct Answer: (A) diffusion current is large and drift current is small.

Solution:

Concept:

- Diffusion current is driven by the large initial concentration gradients across a newly formed p - n junction.
- Drift current is driven by the depletion-region electric field; this field develops as majority carriers diffuse and leave uncovered ions behind.

Step 1: Consider the initial concentration difference At the start, electrons are abundant on the n -side and holes on the p -side. The concentration gradients cause substantial majority-carrier diffusion across the junction. Thus the initial diffusion current is large, ruling out (B) and (D).

Step 2: Consider the developing junction field The depletion layer and potential barrier are only beginning to develop, so the drift current is initially small. This rules out (C), which calls both currents large. As the barrier grows, diffusion is opposed and the reverse drift contribution grows until their magnitudes balance in thermal equilibrium; the question specifically concerns the initial stage.

Step 3: Conclusion Initially the diffusion current is large and the drift current is small. Hence, the correct option is (A).

Quick Tip to Solve: Use the time word initially: the concentration gradient already exists, while the depletion field is still building.

30(iv). An ac voltage $V = 0.5 \sin(100\pi t)$ volt is applied, in turn, across a half-wave rectifier and a full-wave rectifier. The frequency of the output voltage across them respectively will be [1 mark]

- (A) 25 Hz, 50 Hz
- (B) 25 Hz, 100 Hz
- (C) 50 Hz, 50 Hz
- (D) 50 Hz, 100 Hz

Correct Answer: (D) 50 Hz, 100 Hz

Solution:

Concept:

- For an input $V = V_0 \sin(\omega t)$, the frequency is $f = \omega/(2\pi)$.
- A half-wave rectifier produces one output pulse per input cycle; a full-wave rectifier produces two, so their ripple frequencies are f and $2f$.

Step 1: Read the input angular frequency Comparing $V = 0.5 \sin(100\pi t)$ with the standard form gives $\omega = 100\pi \text{ rad s}^{-1}$. Hence

$$f = \frac{100\pi}{2\pi} = 50 \text{ Hz.}$$

The amplitude 0.5 V does not determine the frequency.

Step 2: Count the output pulses The half-wave output repeats after each complete input period, so its frequency remains 50 Hz. The full-wave output repeats after each half-period, so its frequency is 100 Hz. Options (A) and (B) incorrectly halve the half-wave frequency; option (C) fails to double the full-wave frequency.

Step 3: Conclusion The output frequencies are respectively 50 Hz and 100 Hz. Hence, the correct option is (D).

Quick Tip to Solve: Half-wave means half the input cycle is suppressed, not half the repetition frequency; full-wave doubles the pulse frequency.

Section E (15 marks)

31(a)(i). Mention the factors on which the resonant frequency of a series LCR circuit depends. Plot a graph showing variation of impedance of a series LCR circuit with the frequency of the applied a.c. source. [5 marks total]

Solution:

Concept:

- In a series LCR circuit, $Z = \sqrt{R^2 + (\omega L - 1/\omega C)^2}$, where R , L and C are resistance, inductance and capacitance, and $\omega = 2\pi f$.
- Resonance occurs when the inductive and capacitive reactances are equal: $X_L = X_C$. The net reactance then vanishes.

Step 1: Determine the factors controlling resonance At the resonant angular frequency ω_0 , the opposing inductive and capacitive reactances cancel:

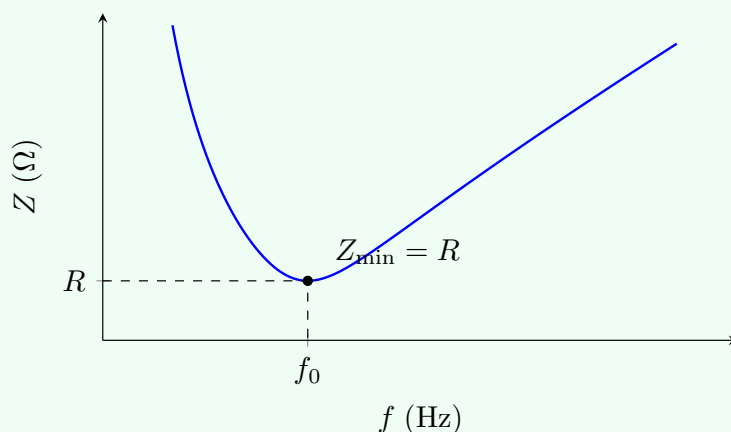
$$\omega_0 L = \frac{1}{\omega_0 C} \Rightarrow \omega_0^2 = \frac{1}{LC} \Rightarrow f_0 = \frac{1}{2\pi\sqrt{LC}}.$$

Thus, the resonant frequency depends on the inductance L and capacitance C . Increasing either decreases f_0 . For the ideal series LCR model, it is independent of R ; resistance controls the minimum impedance and the sharpness of resonance.

Step 2: Sketch impedance against source frequency At very low frequency, $1/(2\pi fC)$ is large, so the circuit is predominantly capacitive and Z is large. As frequency rises towards f_0 , the magnitude of the net reactance falls. At resonance,

$$Z_{\min} = R.$$

Above f_0 , the inductive reactance dominates and the impedance rises again. The curve therefore has a minimum at (f_0, R) ; it does not pass through the origin. The following graph is schematic for a fixed positive resistance.



Series LCR impedance has its minimum R at resonance.

Step 3: Conclusion The resonant frequency is $f_0 = 1/(2\pi\sqrt{LC})$, so it depends on L and C , independently of R in the ideal series LCR model. The impedance-frequency graph has its minimum $Z = R$ at $f = f_0$.

Quick Tip to Solve: Mark the impedance minimum at (f_0, R) , not at zero; on either side the uncompensated reactance makes Z larger.

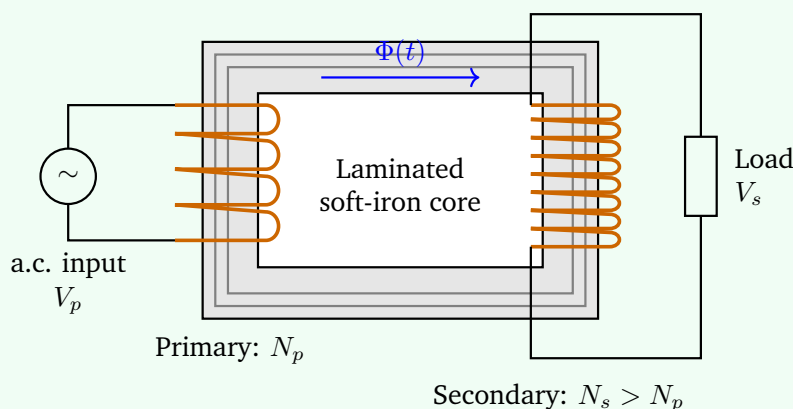
31(a)(ii). With the help of a suitable diagram, explain the working of a step-up transformer.

Solution:

Concept:

- A transformer works by mutual induction: a changing magnetic flux Φ linking each turn induces emf $e = -N d\Phi/dt$ in a winding of N turns.
- A step-up transformer has more secondary turns than primary turns: $N_s > N_p$. In the ideal case, $V_s/V_p = N_s/N_p$, where V_p, V_s are rms input and output voltages.

Step 1: Describe the step-up transformer and its operation Two insulated windings, the primary with N_p turns and the secondary with N_s turns, are wound on a common laminated soft-iron core. In a step-up transformer, $N_s > N_p$. The primary is connected to an a.c. supply and the secondary supplies the load, with no direct electrical connection between the two windings. The alternating primary current establishes a changing flux in the core. This flux links both windings and induces an alternating emf in the secondary by mutual induction. The closed iron core provides a path for the magnetic flux; its laminations reduce eddy-current heating.



Step-up transformer: the secondary has more turns than the primary (schematic).

Step 2: Derive the voltage transformation relation If leakage flux is neglected, the same flux Φ links every turn of both windings. Faraday's law gives

$$e_p = -N_p \frac{d\Phi}{dt}, \quad e_s = -N_s \frac{d\Phi}{dt}.$$

Taking the ratio of emf magnitudes, and neglecting winding voltage drops in an ideal transformer, gives the rms terminal-voltage relation

$$\frac{V_s}{V_p} = \frac{N_s}{N_p} > 1.$$

Thus the secondary voltage exceeds the primary voltage. Ideally, conservation of power gives $V_p I_p = V_s I_s$, so $I_s/I_p = N_p/N_s < 1$: the voltage increase is accompanied by a current decrease. A steady d.c. supply cannot maintain this operation because it does not produce continuously changing flux.

Step 3: Conclusion A step-up transformer uses mutual induction in a common iron core. Since $N_s > N_p$, its secondary a.c. voltage exceeds its primary voltage: $V_s/V_p = N_s/N_p > 1$ ideally.

Quick Tip to Solve: Draw more turns on the secondary, label the common core and a.c. input, and use $V_s/V_p = N_s/N_p$ to establish voltage step-up.

31(a)(iii). Write two causes of energy loss in a real transformer.

Solution:

Concept:

- A real transformer has resistive windings and a conducting magnetic core, so some input electrical energy is converted into heat instead of reaching the load.
- Joule heating in a resistance R carrying rms current I has average power $P = I^2 R$. A changing core flux also induces circulating eddy currents by Faraday's law.

Step 1: Identify copper loss in the windings The primary and secondary coils have finite wire resistances R_p and R_s . Their rms currents I_p and I_s therefore produce heat at the combined rate

$$P_{\text{copper}} = I_p^2 R_p + I_s^2 R_s.$$

This heating is called copper loss and reduces the power delivered to the load. Using low-resistance winding wire reduces it.

Step 2: Identify eddy-current loss in the core The alternating magnetic flux induces closed loops of current within the conducting iron core. These eddy currents dissipate energy as heat because the core has finite electrical resistance. Making the core from thin sheets insulated from one another interrupts large conducting loops and restricts the currents; hence a laminated core reduces this loss.

Step 3: Conclusion Two causes of energy loss are copper loss due to winding resistance and eddy-current heating in the iron core.

Quick Tip to Solve: Keep the locations distinct: copper loss occurs in the windings, whereas eddy-current loss occurs in the core and is reduced by lamination.

OR

31(b)(i). With the help of a diagram, briefly explain the construction and working of ac generator.

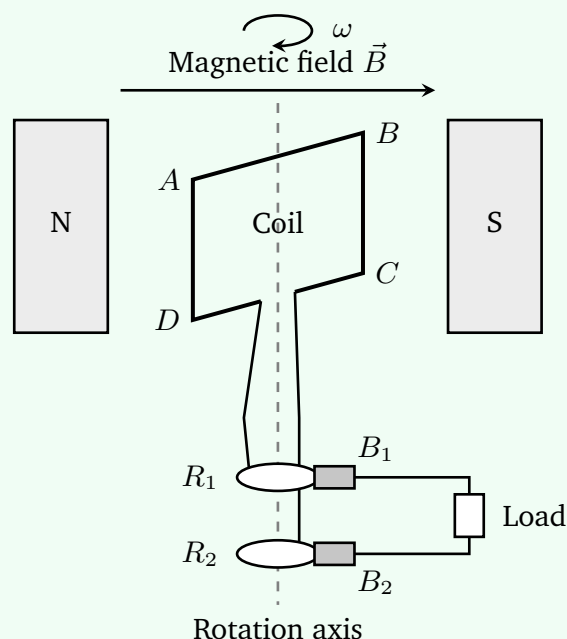
[5 marks total]

Solution:

Concept:

- Faraday's law gives the induced emf, $\mathcal{E} = -d(N\Phi)/dt$, where N is the number of coil turns and Φ is the magnetic flux through one turn.
- For a coil of area A rotating with angular speed ω in a uniform field B , the flux linkage is $NBA \cos \omega t$ when its normal initially lies along the field.

Step 1: Describe the construction of the generator An ac generator converts mechanical energy into electrical energy. A rectangular insulated coil $ABCD$, having N turns and area A , rotates on a shaft between the north and south poles of a strong magnet. The magnetic field $\vec{B}$ is directed from the north pole to the south pole. The two coil ends are connected to two separate, continuous metallic slip rings R_1 and R_2 . The rings rotate with the shaft and are insulated from one another and from the shaft. Stationary carbon brushes B_1 and B_2 press against the rings and connect the coil to the external load. A mechanical drive supplies the energy needed to rotate the coil.



Schematic ac generator: rotating coil, continuous slip rings, stationary brushes and external load.

Step 2: Obtain the alternating emf and explain its reversal Let the shaft rotate uniformly with angular speed ω . Choose $t = 0$ when the normal to the coil is parallel to the magnetic field. At time t , the angle between the field and the coil normal is $\theta = \omega t$, so the flux linkage is

$$N\Phi = NBA \cos \omega t.$$

Applying Faraday's law,

$$\mathcal{E} = -\frac{d}{dt}(NBA \cos \omega t) = NBA\omega \sin \omega t.$$

Thus the peak emf is $\mathcal{E}_0 = NBA\omega$. The emf is zero when the coil normal is parallel to the field, and its magnitude is greatest when the coil plane is parallel to the field. After each half revolution, the motion of each active side relative to the field reverses, so the emf and the current through a resistive load reverse. The slip rings maintain each coil end's connection to the same brush; they do not interchange the connections. Hence the output is alternating, with frequency $f = \omega/(2\pi)$.

Step 3: Conclusion The rotating coil converts mechanical energy into electrical energy and supplies an alternating emf $\mathcal{E} = NBA\omega \sin \omega t$ through slip rings and brushes. The emf reverses every half revolution.

Quick Tip to Solve: Use two continuous slip rings for an ac generator. Measure the flux angle from the coil normal before applying Faraday's law.

31(b)(ii). An electron is revolving around a proton in an orbit of radius r with a speed v . Obtain expression for magnetic moment associated with the electron.

Solution:

Concept:

- A circulating charge has equivalent current $I = e/T$, where e is the positive magnitude of the electron charge and T is its orbital period.

- A current loop has magnetic moment $\mu = IA$, where I is its current and A is its enclosed area. Its direction follows the right-hand rule for conventional current.

Step 1: Find the equivalent orbital current Let e be the positive magnitude of the electron's charge. In one revolution, the electron travels a distance $2\pi r$, giving the orbital period

$$T = \frac{2\pi r}{v}.$$

A charge of magnitude e passes a fixed point of the orbit once in this time. The magnitude of the equivalent conventional current is therefore

$$I = \frac{e}{T} = \frac{ev}{2\pi r}.$$

Because the electron is negatively charged, conventional current circulates in the direction opposite to its motion.

Step 2: Determine the magnetic moment and its direction The circular orbit encloses area $A_{\text{orbit}} = \pi r^2$. Thus the orbital magnetic moment has magnitude

$$\mu = IA_{\text{orbit}} = \frac{ev}{2\pi r} \pi r^2 = \frac{evr}{2}.$$

It is perpendicular to the orbit, in the direction obtained by curling the right-hand fingers along conventional current. If $\vec{L}$ is the electron's orbital angular momentum, then $L = m_e vr$, so

$$\vec{\mu} = -\frac{e}{2m_e} \vec{L}.$$

The negative sign expresses that the magnetic moment is opposite to the electron's orbital angular momentum; this is the orbital contribution.

Step 3: Conclusion The electron's orbital magnetic moment has magnitude $\mu = evr/2$, in A m^2 . Its vector form is $\vec{\mu} = -e\vec{L}/(2m_e)$, so it is opposite to the electron's orbital angular momentum.

Quick Tip to Solve: Find the period $T = 2\pi r/v$, then substitute into $\mu = (e/T)\pi r^2$. Reverse the electron's direction of motion when applying the current-loop right-hand rule.

32(a)(i). A dielectric slab of dielectric constant K and thickness t is inserted between plates of a parallel plate capacitor of plate separation d and plate area A . Obtain an expression for its capacitance. [5 marks total]

Solution:

Concept:

- For a parallel plate capacitor, capacitance is $C = Q/V$, where Q is the magnitude of charge on either plate and V is their potential difference. Edge effects are neglected.
- A dielectric of relative permittivity K reduces the electric field for a given free surface charge density from σ/ϵ_0 to $\sigma/(K\epsilon_0)$. Potential drops through successive layers add.

Step 1: Find the fields in the air and dielectric layers Let the slab cover the full plate area A , with its faces parallel to the plates. If the free charge on a plate is Q , its surface charge density is $\sigma = Q/A$.

The total air thickness is $d - t$, while the dielectric thickness is t . The fields normal to the plates are

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

If air occurs on both sides of the slab, the two air potential drops still add to the drop across the total thickness $d - t$.

Step 2: Add the potential drops and obtain the capacitance Since the field is uniform within each layer, the potential difference is the sum of field times thickness in the two media:

$$\begin{aligned} V &= E_{\text{air}}(d - t) + E_{\text{slab}}t \\ &= \frac{Q}{\epsilon_0 A} \left(d - t + \frac{t}{K} \right), \\ C &= \frac{Q}{V} = \frac{\epsilon_0 A}{d - t + t/K}. \end{aligned}$$

For $t = 0$, this reduces to $\epsilon_0 A/d$, the air capacitor. For $t = d$, it becomes $K \epsilon_0 A/d$, as expected for complete dielectric filling.

Step 3: Conclusion The capacitance is $C = \frac{\epsilon_0 A}{d - t + t/K}$.

Quick Tip to Solve: Replace the dielectric thickness by its electrical equivalent t/K , and add this to the remaining air thickness $d - t$.

32(a)(ii). Two capacitors of different capacitances are connected first (1) in series and then (2) in parallel across a dc source of 100 V. If the total energy stored in the combination in the two cases are 40 mJ and 250 mJ respectively, find the capacitance of the capacitors.

Solution:

Concept:

- The energy stored in a capacitor combination of equivalent capacitance C_{eq} across voltage V is $U = \frac{1}{2} C_{\text{eq}} V^2$.
- For two capacitors, the parallel capacitance is $C_p = C_1 + C_2$, while the series capacitance is $C_s = C_1 C_2 / (C_1 + C_2)$. Both equivalent capacitances are positive.

Step 1: Calculate the equivalent capacitances from the energies In both arrangements, the total combination is connected across 100 V. Hence $C_{\text{eq}} = 2U/V^2$. Converting millijoules to joules gives

$$\begin{aligned} C_s &= \frac{2(40 \times 10^{-3})}{100^2} = 8 \times 10^{-6} \text{ F} = 8 \mu\text{F}, \\ C_p &= \frac{2(250 \times 10^{-3})}{100^2} = 50 \times 10^{-6} \text{ F} = 50 \mu\text{F}. \end{aligned}$$

The series combination has lower capacitance and therefore stores less energy at this same applied voltage.

Step 2: Solve for the individual capacitances Write $C_1 = c_1 \mu\text{F}$ and $C_2 = c_2 \mu\text{F}$. The parallel and series rules give

$$c_1 + c_2 = 50, \quad \frac{c_1 c_2}{c_1 + c_2} = 8, \quad c_1 c_2 = 400.$$

Each numerical capacitance is a root of

$$c^2 - 50c + 400 = 0, \quad (c - 40)(c - 10) = 0.$$

Interchanging the names of the two capacitors does not change either combination. Their sum is $50 \mu\text{F}$, and their series value is $40 \times 10/50 = 8 \mu\text{F}$, confirming both given energies.

Step 3: Conclusion The individual capacitances are $40 \mu\text{F}$ and $10 \mu\text{F}$.

Quick Tip to Solve: Convert both energies into equivalent capacitances first, then use the sum and product of the two unknown capacitances.

OR

32(b)(i). Using Gauss's law, show that the electric field $\vec{E}$ at a point due to a uniformly charged infinite plane sheet is given by $\vec{E} = \frac{\sigma}{2\epsilon_0} \hat{n}$ where symbols have their usual meanings. [5 marks total]

Solution:

Concept:

- Gauss's law states $\oint \vec{E} \cdot d\vec{A} = Q_{\text{enc}}/\epsilon_0$, where $d\vec{A}$ points out of the closed surface and Q_{enc} is its net enclosed charge.
- Translational and rotational symmetry of an infinite uniformly charged plane make its field perpendicular to the plane, with equal magnitudes at corresponding points on its two sides.

Step 1: (i) Choose a Gaussian pillbox across the charged sheet Let the infinite sheet have uniform surface charge density σ . Choose a short cylindrical Gaussian surface whose axis is perpendicular to the sheet, with one flat face of area S on each side. Reflection symmetry gives the same field magnitude E on both faces, while symmetry within the plane forbids a tangential component. For positive σ , the field points away from the sheet on both sides.

The field is parallel to the curved surface, so its flux there is zero. On each flat face, the field is parallel to the outward normal and contributes flux ES . The charge inside the pillbox is σS .

Step 2: (i) Apply Gauss's law and state the field direction Adding the contributions from the two faces and using Gauss's law,

$$ES + ES = \frac{\sigma S}{\epsilon_0}, \quad E = \frac{\sigma}{2\epsilon_0}.$$

If $\hat{n}$ is the unit normal directed from the sheet towards the observation point, the signed vector expression is

$$\vec{E} = \frac{\sigma}{2\epsilon_0} \hat{n}.$$

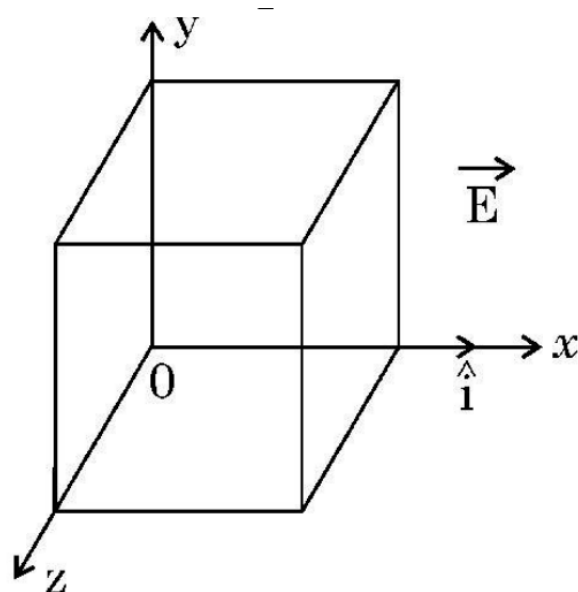
Thus the field points away from a positive sheet and towards a negative sheet. Its magnitude is $|\sigma|/(2\epsilon_0)$, independent of distance, for this ideal infinite sheet.

Step 3: Conclusion The field is $\vec{E} = \frac{\sigma}{2\epsilon_0} \hat{n}$, where $\hat{n}$ is directed normally from the sheet towards the observation point. Its magnitude is independent of distance.

Quick Tip to Solve: Use a pillbox crossing the sheet: both flat faces contribute flux, which produces the factor of two.

Electric field $\vec{E}$ in a region is given by $\vec{E} = (5x^2 + 2)\hat{i}$, where E is in N/C and x is in meters. A cube of side 10 cm is placed in the region as shown in figure.

32(b)(ii)(1). Calculate the electric flux through the cube.



Solution:

Concept:

- Gauss's law states $\oint \vec{E} \cdot d\vec{A} = Q_{\text{enc}}/\epsilon_0$, where $d\vec{A}$ points out of the closed surface and Q_{enc} is its net enclosed charge.
- Flux through a planar face in a uniform field is $EA \cos \theta$, where θ is the angle between the field and the outward normal. Opposite cube faces have opposite outward normals.

Step 1: (ii)(1) Identify the contributing faces of the cube The cube shown has one vertex at the origin and extends in the positive x direction from $x = 0$ to $x = a$, where $a = 10 \text{ cm} = 0.10 \text{ m}$. Its face area is $a^2 = 0.010 \text{ m}^2$. Because $\vec{E} = (5x^2 + 2)\hat{i}$, four faces with normals along the y and z axes contribute zero flux.

On the two faces perpendicular to x , the field is constant over each face. At $x = 0$, $E_x = 2 \text{ N/C}$ and the outward normal is $-\hat{i}$; at $x = 0.10 \text{ m}$, $E_x = 2.05 \text{ N/C}$ and the outward normal is $+\hat{i}$.

Step 2: (ii)(1) Subtract incoming flux from outgoing flux The net outward electric flux is

$$\begin{aligned}\Phi &= E_x(a)a^2 - E_x(0)a^2 \\ &= (2.05 - 2)(0.010) \\ &= 5.0 \times 10^{-4} \text{ N m}^2/\text{C}.\end{aligned}$$

The constant field contribution $2\hat{i}$ cancels between opposite faces. Only the increase in $5x^2$ creates a net outward flux.

Step 3: Conclusion The net outward electric flux through the cube is $\boxed{\Phi = 5.0 \times 10^{-4} \text{ N m}^2/\text{C}}$.

Quick Tip to Solve: For a field directed along x , evaluate only the two faces normal to x : net flux is face area times the difference between the right-face and left-face fields. Convert the cube side to metres before squaring it.

32(b)(ii)(2). Calculate the net charge enclosed by the cube.

Solution:

Concept:

- Gauss's law states $\oint \vec{E} \cdot d\vec{A} = Q_{\text{enc}}/\epsilon_0$, where $d\vec{A}$ points out of the closed surface and Q_{enc} is its net enclosed charge.
- Flux through a planar face in a uniform field is $EA \cos \theta$, where θ is the angle between the field and the outward normal. Opposite cube faces have opposite outward normals.

Step 1: Evaluate the net flux through the closed cube The field is $\vec{E} = (5x^2 + 2)\hat{i}$ in SI units. The cube extends from $x = 0$ to $x = a = 0.10$ m, and its face area is $a^2 = 0.010$ m². Four faces have zero flux since their normals are perpendicular to the field. The two remaining faces have fields 2 N/C and 2.05 N/C. Their outward normals point in opposite directions, so the total outward flux is

$$\Phi = [E_x(a) - E_x(0)]a^2 = (2.05 - 2)(0.010) = 5.0 \times 10^{-4} \text{ N m}^2/\text{C}.$$

Step 2: (ii)(2) Obtain the net enclosed charge Applying Gauss's law to this closed cube,

$$\begin{aligned} Q_{\text{enc}} &= \epsilon_0 \Phi \\ &= (8.854 \times 10^{-12})(5.0 \times 10^{-4}) \\ &= 4.427 \times 10^{-15} \text{ C}. \end{aligned}$$

The charge is positive because the outgoing flux through the right face is greater than the incoming flux through the left face.

Step 3: Conclusion The cube encloses net positive charge $Q_{\text{enc}} \approx +4.43 \times 10^{-15} \text{ C}$.

Quick Tip to Solve: Compute outward flux with opposite signs on opposite faces, then multiply by vacuum permittivity to obtain enclosed charge.

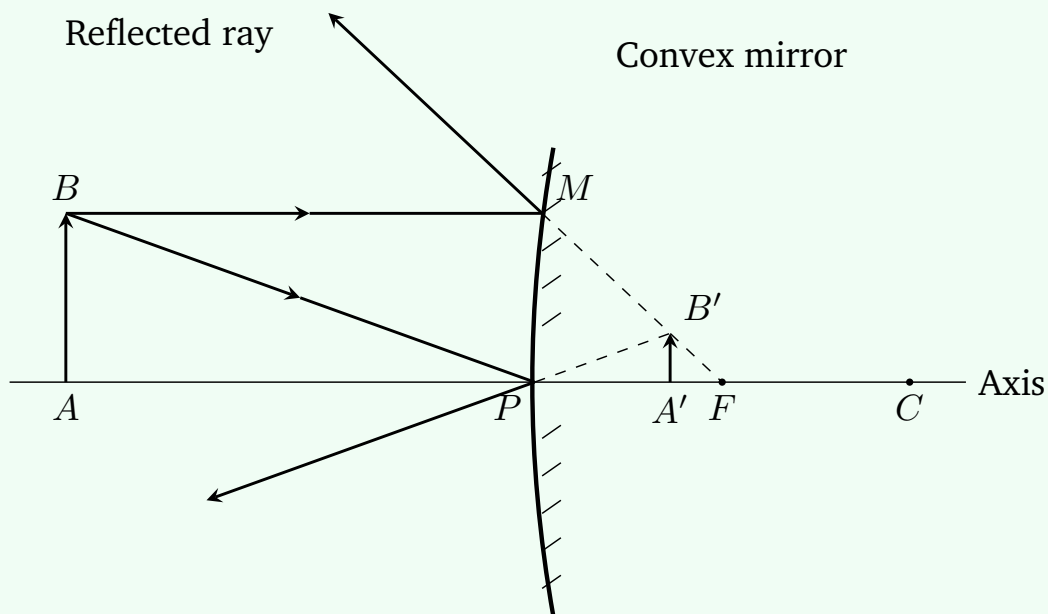
33(a)(i). Draw a ray diagram for the formation of the image of an object by a convex mirror. Hence, obtain the mirror equation. [5 marks total]

Solution:

Concept:

- A convex spherical mirror makes incident parallel paraxial rays diverge as though they came from its principal focus. Reflection obeys $i = r$.
- In the Cartesian convention, a real object in front of a convex mirror has $u < 0$, while its virtual image and focus behind the mirror have $v > 0$ and $f > 0$.

Step 1: (i) Draw the two principal rays Place the upright object AB in front of the convex mirror with pole P , focus F and centre of curvature C . From B , send a ray parallel to the principal axis to M . After reflection it diverges; its backward extension passes through F . Send a second ray from B to P ; it reflects at the same angle to the principal axis. The backward extensions meet at B' , with A' on the axis. Thus the image $A'B'$ lies behind the mirror between P and F . Dashed lines denote backward extensions, not actual transmitted rays.



Convex-mirror image formation (paraxial schematic); dashed lines are virtual extensions.

Step 2: (i) Relate object and image heights using similar triangles Let the positive geometrical distances be $AP = U$, $PA' = V$, $PF = F_0$, and let $AB = h$, $A'B' = h'$. Equal angles at the pole make triangles ABP and $A'B'P$ similar, giving

$$\frac{h'}{h} = \frac{V}{U}.$$

For a small-aperture mirror and paraxial rays, neglect the distance of M from the tangent plane at P , so its height above the axis is h . The similar triangles formed by FM and FB' then give

$$\frac{h'}{h} = \frac{F_0 - V}{F_0}.$$

Equating the ratios and rearranging,

$$\begin{aligned} \frac{V}{U} &= 1 - \frac{V}{F_0}, \\ \frac{1}{U} + \frac{1}{F_0} &= \frac{1}{V}, \\ \frac{1}{F_0} &= \frac{1}{V} - \frac{1}{U}. \end{aligned}$$

Now insert $u = -U$, $v = V$, $f = F_0$ to express this relation in the Cartesian sign convention. The derivation assumes a spherical mirror used with paraxial rays.

Step 3: Conclusion The convex mirror forms a virtual, erect and diminished image between its pole and focus, and obeys

$$\boxed{\frac{1}{f} = \frac{1}{v} + \frac{1}{u}}.$$

Quick Tip to Solve: Derive the mirror relation with positive lengths first, then use the Cartesian signs: real-object distance negative, virtual-image distance positive.

33(a)(ii). Why are multi-component lenses used for both the objective and the eyepiece in optical instruments?

Solution:

Concept:

- Chromatic aberration occurs because refractive index and focal length depend on wavelength, so a single lens forms different colour images at different positions.
- Spherical aberration occurs when marginal and paraxial rays passing through a spherical lens do not meet at the same image point.

Step 1: Combine elements to reduce chromatic aberration An objective or eyepiece containing suitably chosen glasses and lens powers can make the colour-dependent deviations of its individual elements partly compensate each other. This brings different colours closer to a common focus and reduces coloured fringes around the image.

Step 2: Choose shapes to reduce spherical aberration The curvatures and arrangement of the components are chosen so their spherical aberrations compensate, bringing marginal and paraxial rays closer to a common focus. Multi-component designs can also reduce other aberrations across the field. Both the objective, which first forms the image, and the eyepiece, which magnifies it, require this correction for clear viewing.

Step 3: Conclusion Multi-component objectives and eyepieces reduce chromatic and spherical aberrations, giving sharper images with less colour fringing.

Quick Tip to Solve: Name both chromatic and spherical aberrations, then link their reduction to a sharper image in both lens systems.

33(a)(iii). The magnification of a small object produced by a compound microscope is 200. The focal length of the eyepiece is 2 cm and the final image is formed at infinity. Find the magnification produced by the objective.

Solution:

Concept:

- A compound microscope has magnification magnitude $M = |m_o|m_e$. For a final image at infinity, the eyepiece angular magnification is $m_e = D/f_e$, where $D = 25$ cm.
- The objective forms a real inverted intermediate image; its linear magnification is negative in the signed convention. The total magnification given here is a magnitude.

Step 1: Calculate the eyepiece magnification in normal adjustment The final image is at infinity, so the eyepiece is in normal adjustment. Its magnification is

$$m_e = \frac{D}{f_e} = \frac{25 \text{ cm}}{2 \text{ cm}} = 12.5.$$

Step 2: Find the objective magnification The given total magnification is its magnitude. Therefore

$$|m_o| = \frac{M}{m_e} = \frac{200}{12.5} = 16.$$

The objective forms a real inverted intermediate image, so its signed linear magnification is negative. The $1 + D/f_e$ expression would apply to an eyepiece forming its final image at the near point, which

is not the setting given here.

Step 3: Conclusion The objective magnification has magnitude 16 ; its signed value is $m_o = -16$, since the intermediate image is inverted.

Quick Tip to Solve: For a final image at infinity, use eyepiece magnification D/f_e , then divide the total magnification by it.

OR

33(b)(i). Differentiate between a wavefront and a ray.

[5 marks total]

Solution:

Concept:

- A wavefront is a surface of constant phase. In an isotropic medium, a ray gives the direction of propagation and is perpendicular to the wavefront.
- In a homogeneous isotropic medium, the normals to successive wavefronts trace the rays. Wavefront shape and ray direction are complementary descriptions of propagation.

Step 1: Describe a wavefront A wavefront is the locus of all points of a wave that have the same phase at a given instant. It is a surface in three dimensions, not the path followed by a single light disturbance. For a point source in a homogeneous medium, the wavefronts are concentric spheres; far from the source, a small portion can be approximated by a plane.

Step 2: Describe a ray and relate the two descriptions A ray is an imaginary directed line showing the path and direction of propagation of light energy. It is normal to the wavefront in an isotropic medium. Thus plane wavefronts correspond to parallel rays, while spherical wavefronts correspond to radial rays. A wavefront describes equal phase across a surface, whereas a ray describes the direction in which the wave travels.

Step 3: Conclusion A wavefront is an equal-phase surface; a ray is a directed propagation line, normal to the wavefront in an isotropic medium.

Quick Tip to Solve: Use a point source as the example: spherical wavefronts surround it, while rays point radially outwards.

33(b)(ii). State Huygen's principle and verify laws of reflection using suitable diagram.

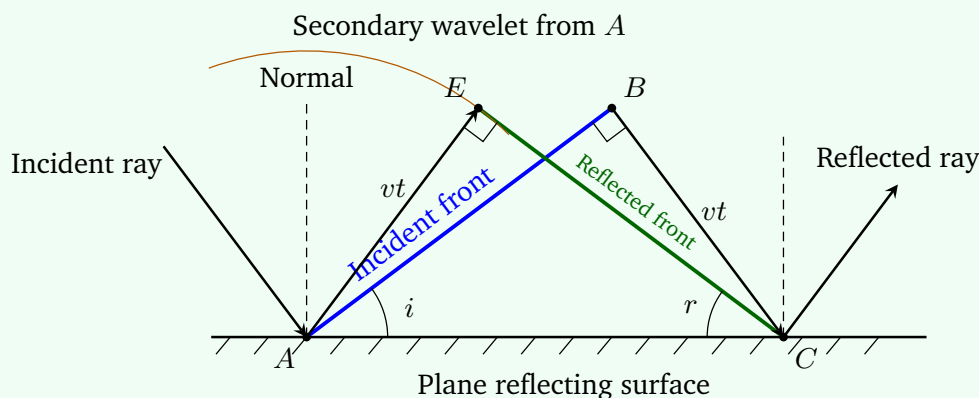
Solution:

Concept:

- A wavefront is a surface of constant phase. In an isotropic medium, a ray gives the direction of propagation and is perpendicular to the wavefront.
- Huygens' principle constructs a later wavefront as the forward envelope of secondary wavelets. In time t , each wavelet travels a radius vt , where v is the wave speed.

Step 1: (ii) State Huygens' principle and construct reflection Every point of a wavefront acts as a source of secondary spherical wavelets spreading through the medium with the wave speed. The forward common tangent surface, or envelope, of these wavelets at a later instant gives the new wavefront. Let the plane incident wavefront AB first meet the plane reflecting surface at A . In the

time t that the disturbance from B travels along the incident ray to C , the reflected secondary wavelet centred at A has radius $AE = vt$. Since incident and reflected waves travel in the same medium, $BC = vt$ also. Draw the tangent CE to the wavelet; it is the reflected wavefront, with $AE \perp CE$. Also $AB \perp BC$, because rays are normal to their wavefronts.



Huygens' construction: $BC = AE = vt$; AB and CE are incident and reflected wavefronts.

Step 2: Verify both laws of reflection The right triangles ABC and AEC share hypotenuse AC and have $BC = AE$, so they are congruent. The angle between the incident wavefront and the surface equals the angle i between the incident ray and the normal; similarly, the angle between the reflected wavefront and the surface equals the reflection angle r . Hence

$$\sin i = \frac{BC}{AC}, \quad \sin r = \frac{AE}{AC}, \quad BC = AE \implies i = r.$$

For a plane reflector in an isotropic medium, the construction is identical in every cross-section perpendicular to the line where the incident wavefront meets the surface. Thus the normals to the incident and reflected wavefronts, and the surface normal at the point of incidence, all lie in one plane. These are the two laws of reflection.

Step 3: Conclusion Huygens' construction verifies $i = r$. The incident ray, reflected ray and normal at incidence lie in the same plane.

Quick Tip to Solve: In the reflection construction compare the two right triangles: their hypotenuse is common and both propagation distances equal vt .

33(b)(iii). In Young's double slit experiment, the slits S_1 and S_2 are 3 mm apart and the screen is placed 1.0 m away from the slits. It is observed that the fourth bright fringe is at a distance of 5 mm from the second dark fringe. Find the wavelength of light used.

Solution:

Concept:

- Young's double-slit fringe width is $\beta = \lambda D/d$, where λ is wavelength, D is screen distance and d is slit separation. Bright fringes are at $n\beta$, and the n th dark fringe is at $(n - \frac{1}{2})\beta$, measured from the central bright fringe.
- The central bright fringe has order zero. On the same side of the centre, the fourth bright and second dark fringes have positions 4β and $3\beta/2$, respectively.

Step 1: (iii) Locate the specified bright and dark fringes Taking the two specified fringes on the same

side of the central maximum, the fourth bright fringe is at $y_{B4} = 4\beta$, while the second dark fringe is at $y_{D2} = \frac{3}{2}\beta$. Their separation is therefore

$$5 \text{ mm} = 4\beta - \frac{3}{2}\beta = \frac{5}{2}\beta, \quad \beta = 2 \text{ mm} = 2 \times 10^{-3} \text{ m}.$$

The central bright fringe has order zero; counting it as the first bright fringe would shift the order incorrectly.

Step 2: Substitute the slit separation and screen distance With $d = 3 \times 10^{-3} \text{ m}$ and $D = 1.0 \text{ m}$,

$$\lambda = \frac{\beta d}{D} = \frac{(2 \times 10^{-3})(3 \times 10^{-3})}{1.0} \text{ m} = 6.0 \times 10^{-6} \text{ m}.$$

This lies in the infrared; the printed numerical data must be used without changing a unit to force a visible wavelength. Strictly, the question does not specify which side of the central fringe is intended. If the two fringes are on opposite sides, their separation is $(4 + \frac{3}{2})\beta$, giving instead $\lambda = \frac{30}{11} \times 10^{-6} \text{ m}$. The usual same-side interpretation gives the value calculated above.

Step 3: Conclusion For the usual same-side interpretation, $\lambda = 6.0 \times 10^{-6} \text{ m} = 6.0 \mu\text{m}$. If opposite sides are intended, the wavelength is $(30/11) \times 10^{-6} \text{ m}$; the question does not explicitly specify the sides.

Quick Tip to Solve: Count bright fringes from order zero and dark fringes from half-order: the fourth bright and second dark are separated by 2.5β on the same side, or 5.5β on opposite sides.