

CBSE Class 12 Physics Question Paper 2025 with Solution PDF-Set 55/2/1



Question Paper with Solutions

Conducted by the Central Board of Secondary Education (CBSE)

Time Allowed: 3 hours

Maximum Marks: 70

General Instructions

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

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

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

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

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

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

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

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

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

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

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

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

$$\text{Boltzman's constant} = 1.38 \times 10^{-23} \text{ JK}^{-1}$$

Section A (16 marks)

1. Two charges $-q$ each are placed at the vertices A and B of an equilateral triangle ABC. If M is the mid-point of AB, the net electric field at C will point along [1 mark]

- (A) CA
- (B) CB
- (C) MC
- (D) CM

Correct Answer: (D) CM

Solution:

Concept:

- The electric field of a negative charge points towards the charge. At distance a , its magnitude is $E = kq/a^2$, where $k = 1/(4\pi\epsilon_0)$ and q is the charge magnitude.
- Electric fields add vectorially. Equal fields symmetrically inclined to a line have cancelling perpendicular components and adding components along that line.

Step 1: Identify the two field directions Since $CA = CB$ and the two charges are equal, the fields at C have equal magnitudes. The charge at A produces a field along CA, while the charge at B produces a field along CB. Both point from C towards the negatively charged vertices.

Step 2: Resolve the fields along the symmetry axis In an equilateral triangle, CM bisects the angle at C. The components parallel to AB cancel, whereas the components towards M add. If the side is a ,

$$E_{\text{net}} = 2 \frac{kq}{a^2} \cos 30^\circ = \frac{\sqrt{3}kq}{a^2}.$$

CA and CB each describe only one field, so (A) and (B) fail. MC points away from the charges and has the opposite sense, so (C) fails.

Step 3: Conclusion The net electric field points from C towards M, along CM. Hence, the correct option is (D).

Quick Tip to Solve: For equal negative charges at A and B, use symmetry to find the perpendicular bisector, then point the resultant towards the midpoint M.

2. A student has three resistors, each of resistance R . To obtain a resistance of $\frac{2}{3}R$, she should connect [1 mark]

- (A) all the three resistors in series.
- (B) all the three resistors in parallel.
- (C) two resistors in series and then this combination in parallel with the third resistor.
- (D) two resistors in parallel and then this combination in series with the third resistor.

Correct Answer: (C) two resistors in series and then this combination in parallel with the third resistor.

Solution:

Concept:

- Resistances in series add: $R_s = R_1 + R_2$. The same current passes through both resistors.

- For two parallel branches, $R_p = R_1 R_2 / (R_1 + R_2)$. Both branches have the same potential difference.

Step 1: Test the mixed connection First connect two of the resistors in series to make a branch of resistance $2R$. Place this branch in parallel with the remaining resistance R . The equivalent resistance is

$$R_{eq} = \frac{(2R)R}{2R + R} = \frac{2R}{3}.$$

This uses all three resistors and gives the required value.

Step 2: Check the other three arrangements All three resistors in series give $3R$, while all three in parallel give $R/3$. Thus (A) and (B) are unsuitable. Two in parallel give $R/2$; adding the third in series gives $R/2 + R = 3R/2$, so (D) is also unsuitable.

Step 3: Conclusion Connect two resistors in series, then connect this combination in parallel with the third resistor. Hence, the correct option is (C).

Quick Tip to Solve: For a target below R , make parallel branches; using branches $2R$ and R immediately gives $2R/3$.

3. A 1 cm straight segment of a conductor carrying 1 A current in x direction lies symmetrically at origin of Cartesian coordinate system. The magnetic field due to this segment at point (1 m, 1 m, 0) is [1 mark]

- (A) $1.0 \times 10^{-9} \hat{k}$ T
 (B) $-1.0 \times 10^{-9} \hat{k}$ T
 (C) $\frac{5.0}{\sqrt{2}} \times 10^{-10} \hat{k}$ T
 (D) $-\frac{5.0}{\sqrt{2}} \times 10^{-10} \hat{k}$ T

Correct Answer: (C) $\frac{5.0}{\sqrt{2}} \times 10^{-10} \hat{k}$ T

Solution:

Concept:

- For a short current segment, the Biot-Savart law gives $\vec{B} \simeq (\mu_0/4\pi)I(\Delta\vec{\ell} \times \vec{r})/r^3$, where $\vec{r}$ points from the segment to the observation point.
- Here $\mu_0/(4\pi) = 10^{-7} \text{ T m A}^{-1}$. The vector product fixes the direction independently of the magnitude calculation.

Step 1: Find the distance and vector product Convert the segment length: $1 \text{ cm} = 10^{-2} \text{ m}$. The current is along positive x, so $\Delta\vec{\ell} = 10^{-2}\hat{i} \text{ m}$. From the origin to the observation point,

$$\vec{r} = (\hat{i} + \hat{j}) \text{ m}, \quad r = \sqrt{2} \text{ m}, \quad \Delta\vec{\ell} \times \vec{r} = 10^{-2}\hat{k} \text{ m}^2.$$

The field is therefore along positive z. Options (B) and (D) have the wrong sign.

Step 2: Substitute in the short-segment formula The segment is much shorter than its distance from the point, so treating it as a current element is appropriate to the printed precision. With $I = 1 \text{ A}$,

$$\vec{B} \simeq 10^{-7} \frac{1 \times 10^{-2}}{(\sqrt{2})^3} \hat{k} = \frac{5.0}{\sqrt{2}} \times 10^{-10} \hat{k} \text{ T}.$$

Option (A) omits the geometric factor from the distance and angle and has the wrong magnitude.

Step 3: Conclusion $\vec{B} = \frac{5.0}{\sqrt{2}} \times 10^{-10} \hat{k}$ T to the stated precision. Hence, the correct option is (C).

Quick Tip to Solve: Use $\hat{i} \times (\hat{i} + \hat{j}) = \hat{k}$ for the sign, then retain r^3 when using the displacement vector form of Biot-Savart's law.

4. The magnetic field due to a small magnetic dipole of dipole moment 'M' at a distance 'r' from the centre along the axis of the dipole is given by [1 mark]

- (A) $\frac{\mu_0}{4\pi} \times \frac{2M}{r^3}$
(B) $\frac{\mu_0}{4\pi} \times \frac{M}{r^3}$
(C) $\frac{\mu_0}{4\pi} \times \frac{M}{2r^3}$
(D) $\frac{\mu_0}{4\pi} \times \frac{2M}{r^2}$

Correct Answer: (A) $\frac{\mu_0}{4\pi} \times \frac{2M}{r^3}$

Solution:

Concept:

- For a small magnetic dipole of moment magnitude M , the axial field at distance r in vacuum is $B_{\text{axial}} = (\mu_0/4\pi)(2M/r^3)$.
- The equatorial field magnitude is $B_{\text{equatorial}} = (\mu_0/4\pi)(M/r^3)$. Thus the axial field is twice the equatorial field at equal distance.

Step 1: Apply the dipole field on the axis On the axial line, $(\vec{M} \cdot \hat{r})\hat{r} = \vec{M}$, on either side of the dipole. Using the dipole-field expression,

$$\vec{B} = \frac{\mu_0}{4\pi r^3} \left[3(\vec{M} \cdot \hat{r})\hat{r} - \vec{M} \right],$$

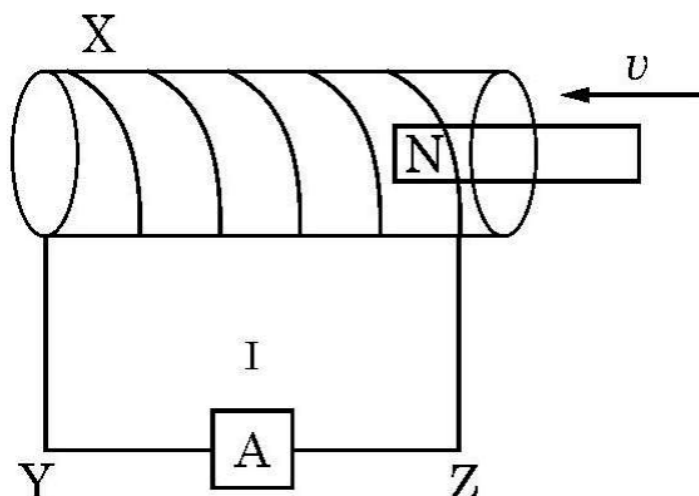
the bracket reduces to $2\vec{M}$. Its magnitude is consequently $(\mu_0/4\pi)(2M/r^3)$.

Step 2: Check the coefficient and distance dependence Option (B) gives the equatorial magnitude and misses the axial factor of two. Option (C) is only one quarter of the axial value. Option (D) incorrectly uses r^{-2} : the field of a small dipole varies as r^{-3} , owing to the cancellation between its opposite poles at large distances.

Step 3: Conclusion The axial field is $B = \frac{\mu_0}{4\pi} \frac{2M}{r^3}$. Hence, the correct option is (A).

Quick Tip to Solve: Remember the axial-to-equatorial field magnitude ratio 2 : 1; both dipole fields have the same inverse-cube dependence on distance.

5. In the figure X is a coil wound over a hollow wooden pipe. A permanent magnet is pushed at a constant speed v from the right into the pipe and it comes out at the left end of the pipe. During the entry and the exit of the magnet, the current in the wire YZ will be from [1 mark]



- (A) Y to Z and then Y to Z
- (B) Z to Y and then Y to Z
- (C) Y to Z and then Z to Y
- (D) Z to Y and then Z to Y

Correct Answer: (B) Z to Y and then Y to Z

Solution:

Concept:

- Lenz's law states that the induced current creates a magnetic field opposing the change in magnetic flux through the coil.
- A coil face is a north pole when the current is anticlockwise as viewed from that face. The printed winding determines how this circulation corresponds to current in YZ.

Step 1: Determine the current during entry The north pole enters from the right. Its field through the coil points towards the left and its flux increases during entry. The induced field must therefore point towards the right: the right face becomes a north pole and repels the approaching north pole. For the winding shown, this requires current through the coil from its Y-connected end to its Z-connected end. In the external wire YZ, the return current is consequently from Z to Y.

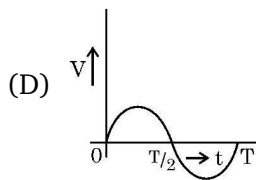
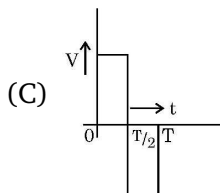
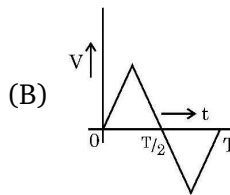
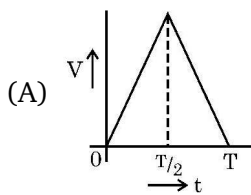
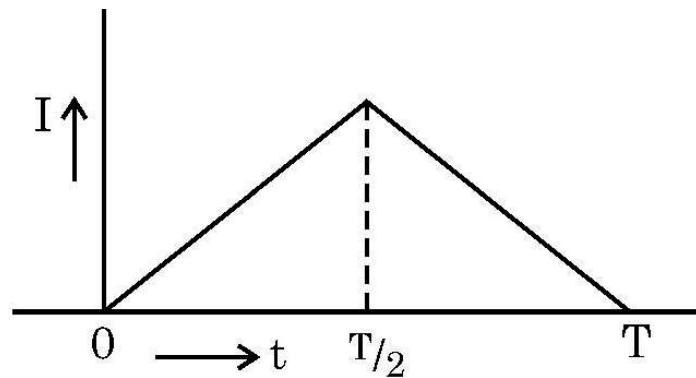
Step 2: Reverse the current during exit As the magnet leaves the left end, the leftward magnetic flux through the coil decreases. The induced field must now point left to maintain this flux. Thus the induced polarity and current reverse, making the current in YZ flow from Y to Z. Options (A) and (D) incorrectly keep the same current direction in both stages, while (C) reverses the correct order.

Step 3: Conclusion The current in wire YZ is from Z to Y during entry and from Y to Z during exit. Hence, the correct option is (B).

Quick Tip to Solve: First choose the induced pole that opposes entry or exit, then trace the drawn winding; current in the return wire has the opposite end-to-end sense to current through the coil.

6. The alternating current I in an inductor is observed to vary with time t as shown in the graph for a cycle. Which one of the following graphs is the correct representation of wave form of voltage V with time t ?

[1 mark]



Correct Answer: (C)

Solution:

Concept:

- The applied voltage across an ideal inductor is $V = L dI/dt$, where L is its inductance; voltage follows the slope of the current graph.
- Constant positive and negative slopes give constant positive and negative voltages, respectively.

Step 1: Differentiate the rising half-cycle Let the peak current be I_0 . Over the first half-cycle, the current rises uniformly from zero to I_0 :

$$\frac{dI}{dt} = \frac{I_0}{T/2} = \frac{2I_0}{T}, \quad V = \frac{2LI_0}{T} > 0.$$

The voltage is constant and positive.

Step 2: Differentiate the falling half-cycle From $T/2$ to T , the slope is $-2I_0/T$, giving the constant negative voltage $-2LI_0/T$. Options (A) and (B) have sloping voltage segments and (D) is sinusoidal; none matches the constant current slopes.

Step 3: Conclusion The voltage is a positive rectangular pulse over the first half-cycle and an equal negative pulse over the second. Hence, the correct option is (C).

Quick Tip to Solve: Replace each straight segment of the current graph by a horizontal voltage level proportional to its slope; rising means positive and falling means negative.

7. A transformer is connected to a 200 V ac source. The transformer supplies 3000 V to a device. If the number of turns in the primary coil is 450, then the number of turns in its secondary coil is [1 mark]

- (A) 30
- (B) 450
- (C) 4500
- (D) 6750

Correct Answer: (D) 6750

Solution:

Concept:

- For an ideal transformer, $V_s/V_p = N_s/N_p$, where V_p, V_s are the primary and secondary voltages and N_p, N_s their respective turn counts.
- A step-up transformer has $V_s > V_p$ and therefore $N_s > N_p$. The voltage per turn is the same in both windings.

Step 1: Identify the voltage ratio The primary is connected to the 200 V source and the secondary supplies 3000 V. Thus,

$$\frac{V_s}{V_p} = \frac{3000}{200} = 15.$$

The secondary must have fifteen times as many turns as the primary.

Step 2: Calculate the secondary turn count Substituting $N_p = 450$ into the transformer relation gives

$$N_s = N_p \frac{V_s}{V_p} = 450 \times 15 = 6750.$$

Option (A), 30, comes from inverting the ratio and would step the voltage down. Option (B), 450, gives no voltage change. Option (C), 4500, gives a ratio of 10 and only 2000 V, rather than 3000 V.

Step 3: Conclusion The secondary coil requires 6750 turns. Hence, the correct option is (D).

Quick Tip to Solve: Compute the step-up factor first: $3000/200 = 15$. Multiply the primary turn count by 15, and check that the secondary has more turns.

8. Which one of the following statements is correct? Electric field due to static charges is [1 mark]

- (A) conservative and field lines do not form closed loops.
- (B) conservative and field lines form closed loops.
- (C) non-conservative and field lines do not form closed loops.
- (D) non-conservative and field lines form closed loops.

Correct Answer: (A) conservative and field lines do not form closed loops.

Solution:

Concept:

- An electrostatic field is conservative: the work done on a charge depends only on its initial and final positions.
- The electric field and potential are related by $\vec{E} = -\nabla V$; hence potential decreases along a field line.

Step 1: Check the conservative property Static charges produce a time-independent electrostatic field. For any closed path,

$$\oint \vec{E} \cdot d\vec{l} = 0.$$

Thus the work done in moving a test charge around the path is zero. Options (C) and (D), which call this field non-conservative, are incorrect.

Step 2: Examine whether field lines can close An electrostatic field line points toward decreasing potential. It cannot return to its starting point while potential keeps decreasing, so it cannot form a closed loop. Field lines begin on positive charges and end on negative charges, or extend to infinity. Option (B) has the correct conservative property but the wrong statement about closed loops.

Step 3: Conclusion The electric field due to static charges is conservative, and its field lines do not form closed loops. Hence, the correct option is (A).

Quick Tip to Solve: For static charges, combine zero work around a closed path with decreasing potential along every field line.

9. A tub is filled with a transparent liquid to a height of 30.0 cm. The apparent depth of a coin lying at the bottom of the tub is found to be 16.0 cm. The speed of light in the liquid will be [1 mark]

(A) $1.6 \times 10^8 \text{ m s}^{-1}$

(B) $2.0 \times 10^8 \text{ m s}^{-1}$

(C) $3.0 \times 10^8 \text{ m s}^{-1}$

(D) $2.5 \times 10^8 \text{ m s}^{-1}$

Correct Answer: (A) $1.6 \times 10^8 \text{ m s}^{-1}$

Solution:

Concept:

- For near-normal viewing from air through a plane liquid surface, refractive index is $\mu = d/d'$, where d and d' are the real and apparent depths.
- The refractive index is also $\mu = c/v$, where c is the speed of light in vacuum and v is its speed in the liquid.

Step 1: Determine the refractive index The coin is at the bottom, so its real depth equals the liquid height. Both depths have the same unit and can be divided directly:

$$\mu = \frac{30.0}{16.0} = 1.875.$$

The apparent depth is smaller because rays emerging into air bend away from the normal.

Step 2: Calculate and compare the light speeds Substitute $c = 3.0 \times 10^8 \text{ m s}^{-1}$:

$$v = \frac{c}{\mu} = 3.0 \times 10^8 \times \frac{16.0}{30.0} = 1.6 \times 10^8 \text{ m s}^{-1}.$$

Options (B), (C) and (D) would imply refractive indices 1.5, 1 and 1.2, respectively. None matches the observed depth ratio; option (C) would also imply no apparent shallowing at all.

Step 3: Conclusion The speed of light in the liquid is $1.6 \times 10^8 \text{ m s}^{-1}$. Hence, the correct option is (A).

Quick Tip to Solve: Use $v = c(\text{apparent depth})/(\text{real depth})$; keeping both depths in centimetres is sufficient.

10. Atomic spectral emission lines of hydrogen atom are incident on a zinc surface. The lines which can emit photoelectrons from the surface are members of [1 mark]

- (A) Balmer series
- (B) Paschen series
- (C) Lyman series
- (D) Neither Balmer, nor Paschen nor Lyman series

Correct Answer: (C) Lyman series

Solution:

Concept:

- Photoelectric emission requires a photon energy $h\nu \geq \phi$, where ϕ is the metal's work function and h is Planck's constant. Zinc requires ultraviolet radiation, with a work function of about 4.3 eV.
- Hydrogen emission energies obey $E_\gamma = 13.6(1/n_f^2 - 1/n_i^2) \text{ eV}$, where $n_i > n_f$. The Lyman, Balmer and Paschen series end at $n_f = 1, 2, 3$, respectively.

Step 1: Compare Balmer and Paschen photons with the threshold The largest photon energy in a series occurs at its limit, $n_i \rightarrow \infty$. The Balmer limit is $13.6/4 = 3.4 \text{ eV}$, and the Paschen limit is $13.6/9 \simeq 1.51 \text{ eV}$. Even these limiting energies are below the zinc work function, so no lines in either series can eject electrons. Options (A) and (B) fail.

Step 2: Test the least energetic Lyman line The smallest Lyman photon energy corresponds to the transition $n_i = 2$ to $n_f = 1$:

$$E_\gamma = 13.6 \left(1 - \frac{1}{4} \right) = 10.2 \text{ eV}.$$

This already exceeds the zinc threshold; higher Lyman lines have still greater photon energies. Hence the statement in option (D), excluding all three series, is incorrect.

Step 3: Conclusion The hydrogen lines capable of ejecting photoelectrons from zinc belong to the Lyman series. Hence, the correct option is (C).

Quick Tip to Solve: Compare the Balmer series limit with the metal threshold first; Lyman photons are much more energetic ultraviolet photons.

11. The energy of an electron in a hydrogen atom in ground state is -13.6 eV . Its energy in an orbit corresponding to quantum number n is -0.544 eV . The value of n is [1 mark]

- (A) 2
- (B) 3
- (C) 4
- (D) 5

Correct Answer: (D) 5

Solution:

Concept:

- In the Bohr model, the energy of hydrogen in level n is $E_n = E_1/n^2$, where $E_1 = -13.6 \text{ eV}$ is the ground-state energy.
- The principal quantum number n is a positive integer. Bound-state energies are negative, with zero energy assigned to a free electron at infinite separation.

Step 1: Form the ratio of the energies Rearrange the energy formula and insert the given values:

$$n^2 = \frac{E_1}{E_n} = \frac{-13.6}{-0.544} = 25.$$

The two negative signs cancel. Both energies are in electronvolts, so their ratio is dimensionless; no conversion to joules is needed.

Step 2: Choose the physical quantum number Taking the positive square root gives $n = \sqrt{25} = 5$. A negative root is not an allowed principal quantum number. As a check, $-13.6/5^2 = -0.544 \text{ eV}$. Options (A), (B) and (C), with $n = 2, 3, 4$, give energies -3.4 , approximately -1.51 , and -0.85 eV , respectively, and therefore do not match the stated level.

Step 3: Conclusion The required principal quantum number is $n = 5$. Hence, the correct option is (D).

Quick Tip to Solve: Divide the ground-state energy by the given energy, cancel their negative signs, and then take the positive square root.

12. When the resistance measured between p and n ends of a p-n junction diode is high, it can act as a/an [1 mark]

- (A) resistor
- (B) inductor
- (C) capacitor
- (D) switch

Correct Answer: (D) switch

Solution:

Concept:

- A p-n junction has high resistance under reverse bias because its depletion region widens and majority-carrier conduction is suppressed.
- An electronic switch has a conducting ON state and a nearly nonconducting OFF state. A diode approximates these states under forward and reverse bias, respectively.

Step 1: Identify the high-resistance junction condition High resistance indicates reverse bias under normal diode operation, below breakdown. Only a very small reverse current flows, and the depletion region contains almost no mobile charge carriers. The p and n regions on its two sides remain conducting.

Step 2: Identify the corresponding switch state Very high terminal resistance means almost no current passes, so the diode acts like an open switch in its OFF state. Under forward bias, its much lower resistance allows conduction, corresponding approximately to the ON state. It is not an ordinary ohmic resistor because its current-voltage relation is nonlinear, and the stated observation does not identify inductive behaviour. A reverse-biased junction also has depletion capacitance, but the resistance measurement here tests conduction, not charge storage; its direct switching interpretation is an open switch.

Step 3: Conclusion The high-resistance p-n junction acts as an open switch, corresponding to the OFF state. Hence, the correct option is (D).

Quick Tip to Solve: Translate high measured resistance into negligible current: the diode is OFF, like an open switch.

13. Assertion (A): In a semiconductor diode the thickness of depletion layer is not fixed.

Reason (R): Thickness of depletion layer in a semiconductor device depends upon many factors such as biasing of the semiconductor. [1 mark]

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

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

Solution:

Concept:

- The depletion layer is the region near a p-n junction depleted of mobile carriers; its fixed ionised donors and acceptors produce the junction barrier field.
- The depletion width depends on junction doping and applied bias. Forward bias reduces the barrier and depletion width, while reverse bias increases them.

Step 1: Evaluate the assertion Assertion (A) is true. The depletion layer is not a material layer of permanently fixed thickness. Its boundaries move as the balance between the junction field and mobile charge carriers changes, so its width can change with the operating conditions.

Step 2: Evaluate the reason Reason (R) is also true. Biasing is one factor that changes the depletion width: forward bias opposes the built-in barrier and narrows the layer, whereas reverse bias strengthens the barrier and widens it. Doping levels also influence the width.

Step 3: Test the explanatory connection The dependence on bias and other junction conditions directly explains why the thickness is not fixed. Therefore, option (B) is incorrect because an explanatory connection does exist, while options (C) and (D) wrongly classify at least one true statement as false.

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

Quick Tip to Solve: Recall the paired changes: forward bias narrows the depletion layer; reverse bias widens it. This proves the width is variable.

14. Assertion (A): In Bohr model of hydrogen atom, the angular momentum of an electron in n^{th} orbit is proportional to the square root of its orbit radius r_n .

Reason (R): According to Bohr model, electron can jump to its nearest orbits only. [1 mark]

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

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

Solution:

Concept:

- In the Bohr model, Coulomb attraction provides centripetal force: $mv^2/r = ke^2/r^2$, where $k = 1/(4\pi\epsilon_0)$, m is electron mass and e is the elementary charge.
- Orbital angular momentum is $L = mvr$. A transition between allowed energy levels involves a photon of energy $h\nu = |E_i - E_f|$; the levels need not be adjacent.

Step 1: Evaluate the assertion using the orbital dynamics Multiply the centripetal-force relation by mr^3 to connect angular momentum and orbital radius:

$$L^2 = m^2 v^2 r^2 = m k e^2 r, \quad L = \sqrt{m k e^2} \sqrt{r}.$$

Since m , k and e are constants, $L \propto \sqrt{r_n}$ for hydrogen. Assertion (A) is therefore true. This also agrees with $L_n \propto n$ and $r_n \propto n^2$.

Step 2: Evaluate the restriction stated in the reason Reason (R) is false. Bohr's model does not restrict an electron to transitions between nearest orbits. For example, the transition from $n = 3$ directly to $n = 1$ emits a photon with the corresponding energy difference and skips the intermediate orbit.

Step 3: Test whether the reason explains the assertion A false restriction on transitions cannot explain the true relation between angular momentum and radius. That relation follows from orbital dynamics, as derived above. Options (A) and (B) incorrectly call the reason true; option (D) incorrectly calls the assertion false.

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

Quick Tip to Solve: Combine $L_n \propto n$ with $r_n \propto n^2$; also remember that Bohr transitions can skip intermediate orbits.

15. Assertion (A): Out of Infrared and radio waves, the radio waves show more diffraction effect.

Reason (R): Radio waves have greater frequency than infrared waves.

[1 mark]

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

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

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

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

Solution:

Concept:

- Diffraction is the spreading of waves around obstacles or through apertures. For the same obstacle or aperture size a , its extent increases with the ratio λ/a , where λ is wavelength.
- Electromagnetic waves in vacuum obey $c = \nu\lambda$, where c is their common speed and ν their frequency. A longer wavelength therefore means a lower frequency.

Step 1: Test the assertion Radio waves have much longer wavelengths than infrared waves. For comparable obstacles, their larger wavelength produces more appreciable bending and spreading. Thus Assertion (A) is true.

Step 2: Test the reason Since $\nu = c/\lambda$, the longer wavelength of radio waves gives them a smaller frequency than infrared waves. The stated claim that radio waves have a greater frequency is therefore false.

Step 3: Check the explanatory link The assertion is explained by the greater wavelength of radio waves, whereas the printed reason gives the opposite frequency ordering. Options (A) and (B) require a true reason and option (D) requires a false assertion, so none of these codes applies.

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

Quick Tip to Solve: For the same obstacle, compare wavelengths first: the longer-wavelength radio wave diffracts more and has the lower frequency.

16. Assertion (A): In an ideal step-down transformer, the electrical energy is not lost.

Reason (R): In a step-down transformer, voltage decreases but the current increases.

[1 mark]

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

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

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

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

Solution:

Concept:

- An ideal transformer has no winding, eddy-current, hysteresis or magnetic-flux losses. Its input and output powers are equal: $V_p I_p = V_s I_s$, with p and s denoting primary and secondary quantities.

- For an ideal transformer, $V_s/V_p = N_s/N_p$ and $I_s/I_p = N_p/N_s$, where N_p and N_s are the numbers of turns. Voltage and current transform in inverse ratios.

Step 1: Test the assertion The word ideal means that the transformer transfers all the electrical energy it receives to its output. Stepping down the voltage does not imply loss of energy. The assertion is true.

Step 2: Test the reason A step-down transformer has $N_s < N_p$, so $V_s < V_p$. Its secondary current is correspondingly larger: $I_s/I_p = N_p/N_s > 1$. The reason is true for the stated ideal transformer supplying a load.

Step 3: Relate the voltage and current changes to energy The current increases by exactly the factor by which the voltage decreases, so

$$V_s I_s = \left(V_p \frac{N_s}{N_p} \right) \left(I_p \frac{N_p}{N_s} \right) = V_p I_p.$$

Equal powers deliver equal energies during the same time interval. Thus the reason explains why a smaller output voltage is consistent with no energy loss. Option (B) misses this link, while options (C) and (D) incorrectly treat one or both statements as false.

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

Quick Tip to Solve: In an ideal transformer compare the product VI : stepping voltage down steps current up in the reciprocal ratio.

Section B (10 marks)

17(a). Two wires of the same material and the same radius have their lengths in the ratio 2 : 3. They are connected in parallel to a battery which supplies a current of 15 A. Find the current through the wires. [2 marks]

Solution:

Concept:

- A uniform wire has resistance $R = \rho L/A$, where ρ is resistivity, L is length and A is cross-sectional area. The same material and radius give the same ρ and A .
- Parallel branches have the same potential difference. Hence $I = V/R$ makes branch currents inversely proportional to their resistances, and Kirchhoff's junction rule gives the total current as the sum of branch currents.

Step 1: Express the resistance ratio Let subscripts 1 and 2 refer to the wires whose lengths are in the ratio $L_1 : L_2 = 2 : 3$. Since ρ and $A = \pi r^2$ are common to both,

$$\frac{R_1}{R_2} = \frac{\rho L_1/A}{\rho L_2/A} = \frac{2}{3}.$$

Thus the shorter wire has the smaller resistance.

Step 2: Divide the supplied current The voltage across both wires is the same, so

$$\frac{I_1}{I_2} = \frac{V/R_1}{V/R_2} = \frac{R_2}{R_1} = \frac{3}{2}.$$

Write $I_1 = 3k$ and $I_2 = 2k$. The battery supplies 15 A, giving

$$3k + 2k = 15 \text{ A}, \quad k = 3 \text{ A}.$$

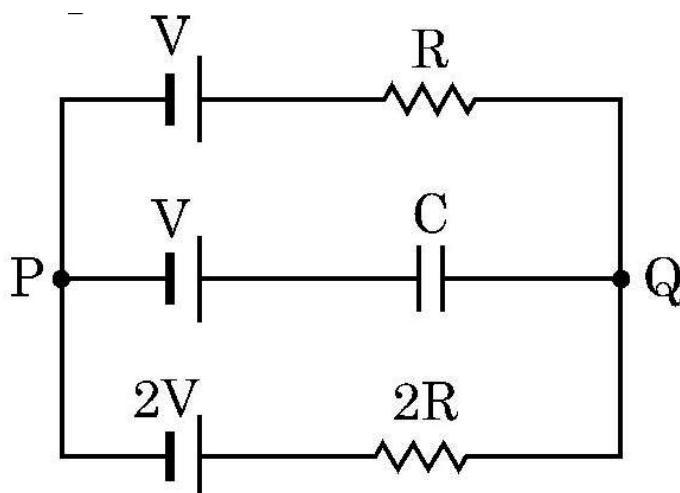
Substitution into the two branch expressions gives $I_1 = 9 \text{ A}$ and $I_2 = 6 \text{ A}$; their sum checks the stated supply current.

Step 3: Conclusion The shorter wire carries 9 A, and the longer wire carries 6 A.

Quick Tip to Solve: With equal material and radius, reverse the length ratio to obtain the parallel-current ratio, then divide the total current in that ratio.

OR

17(b). In the circuit three ideal cells of e.m.f. V , V and $2V$ are connected to a resistor of resistance R , a capacitor of capacitance C and another resistor of resistance $2R$ as shown in figure. In the steady state find (i) the potential difference between P and Q and (ii) potential difference across capacitor C . [2 marks]



Solution:

Concept:

- In the steady state of a direct-current circuit, a capacitor carries no current. Its branch is open for finding the current in the remaining resistive loop, but its final potential difference can be nonzero.
- Kirchhoff's loop rule states that the algebraic sum of potential changes around a closed loop is zero. Across a cell from its short to long plate the potential rises by its emf; across a resistor along the current it falls by IR .

Step 1: Find the steady outer-loop current In the printed circuit, all three cells have their positive terminals on the right. The capacitor branch carries no steady current. The lower cell of emf $2V$ drives current I from P to Q through $2R$, returning from Q to P through the upper resistor R and opposing cell V . Kirchhoff's loop rule gives

$$2V - 2IR - IR - V = 0, \quad I = \frac{V}{3R}.$$

This positive value confirms the assumed current direction.

Step 2: Calculate the potential difference between P and Q Let U_P and U_Q denote the node potentials, reserving V for the stated cell emf. Along the lower branch from P to Q,

$$U_Q - U_P = 2V - I(2R) = 2V - \frac{2V}{3} = \frac{4V}{3}.$$

The upper branch provides the same check: travelling from P to Q is opposite to the current in R , so its potential change is $V + IR = 4V/3$.

Step 3: Calculate the capacitor potential difference Call the left capacitor plate X. The middle cell fixes its potential at $U_X = U_P + V$, while the right plate is connected directly to Q. Therefore

$$U_Q - U_X = (U_Q - U_P) - V = \frac{4V}{3} - V = \frac{V}{3}.$$

The right plate, connected to Q, is at the higher potential. The capacitance determines the final charge, not this steady-state voltage.

Step 4: Conclusion (i) Q is $4V/3$ above P: $U_Q - U_P = 4V/3$, or $U_P - U_Q = -4V/3$. (ii) The capacitor voltage has magnitude $V/3$, with its Q-side plate positive.

Quick Tip to Solve: First open the capacitor branch to solve the resistive loop; then use the middle cell's polarity to subtract its emf from the P-to-Q voltage.

18. In a double-slit experiment, 6th dark fringe is observed at a certain point of the screen. A transparent sheet of thickness t and refractive index n is now introduced in the path of one of the two interfering waves to increase its phase by $2\pi(n - 1)t/\lambda$. The pattern is shifted and 8th bright fringe is observed at the same point. Find the relation for thickness t in terms of n and λ . [2 marks]

Solution:

Concept:

- In Young's double-slit experiment, the m^{th} dark fringe has path difference $(m - \frac{1}{2})\lambda$, whereas the m^{th} bright fringe has path difference $m\lambda$. Here λ is the wavelength and the central bright fringe has order zero.
- A transparent sheet of thickness t and refractive index n adds optical path $(n - 1)t$, corresponding to the stated phase change $\phi = 2\pi(n - 1)t/\lambda$.

Step 1: Write the two fringe conditions Before inserting the sheet, the point is at the sixth dark fringe. Its initial path difference and corresponding phase difference are

$$\Delta_1 = \left(6 - \frac{1}{2}\right)\lambda = \frac{11\lambda}{2}, \quad \phi_1 = 11\pi.$$

After the stated increase, the point is at the eighth bright fringe, for which

$$\Delta_2 = 8\lambda, \quad \phi_2 = 16\pi.$$

The dark-fringe count starts at $\lambda/2$, so its sixth order must not be replaced by 6λ .

Step 2: Equate the sheet contribution to the change The sheet must supply the increase between

these conditions:

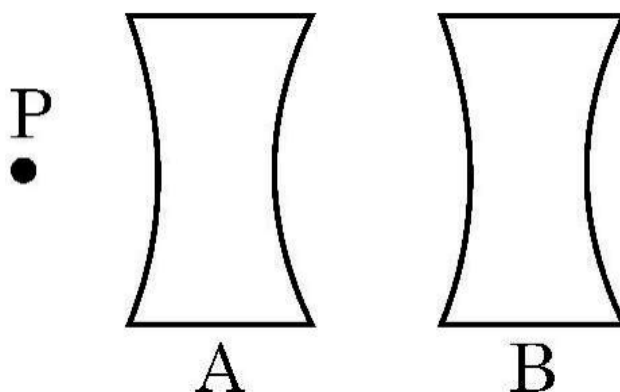
$$\begin{aligned}(n-1)t &= \Delta_2 - \Delta_1 \\ &= 8\lambda - \frac{11\lambda}{2} = \frac{5\lambda}{2}.\end{aligned}$$

Equivalently, the phase increment is $16\pi - 11\pi = 5\pi$; substituting it into $2\pi(n-1)t/\lambda$ gives the same relation. The screen point remains fixed while insertion of the sheet shifts the fringe pattern.

Step 3: Conclusion The required thickness is $t = \frac{5\lambda}{2(n-1)}$.

Quick Tip to Solve: Convert the sixth dark fringe to order 5.5, then subtract it from bright order 8; the sheet adds 2.5 wavelengths of optical path.

19. Two concave lenses A and B, each of focal length 8.0 cm are arranged coaxially 16 cm apart as shown in figure. An object P is placed at a distance of 4.0 cm from A. Find the position and nature of the final image formed. [2 marks]



Solution:

Concept:

- With incident light travelling from left to right, the Cartesian lens formula is $1/v - 1/u = 1/f$, where u and v are measured from the lens. A concave lens has negative focal length.
- The image formed by the first lens acts as the object for the second lens. The total transverse magnification is $m = m_A m_B$, where each lens has $m = v/u$.

Step 1: Locate the image formed by lens A For lens A, the real object is to its left, so $u_A = -4.0$ cm and $f_A = -8.0$ cm. Thus

$$\frac{1}{v_A} = \frac{1}{f_A} + \frac{1}{u_A} = -\frac{1}{8} - \frac{1}{4} = -\frac{3}{8}, \quad v_A = -\frac{8}{3} \text{ cm.}$$

This intermediate image is virtual and lies to the left of A. The rays reaching B diverge as though they came from this point.

Step 2: Use the intermediate image as the object for B Lens B is 16 cm to the right of A. Its object therefore lies $16 + 8/3 = 56/3$ cm to its left, giving $u_B = -56/3$ cm. Applying the formula again,

$$\frac{1}{v_B} = -\frac{1}{8} - \frac{3}{56} = -\frac{5}{28}, \quad v_B = -\frac{28}{5} \text{ cm.}$$

To establish the image nature, calculate

$$m_A = \frac{-8/3}{-4} = \frac{2}{3}, \quad m_B = \frac{-28/5}{-56/3} = \frac{3}{10}, \quad m = \frac{1}{5}.$$

The negative image distance from B means that the emergent rays meet only on backward extension. The positive total magnification indicates an erect image, and its magnitude is less than one.

Step 3: Conclusion The final image is 5.6 cm to the left of B, or 10.4 cm to the right of A, between the lenses. It is virtual, erect and diminished, with magnification $+1/5$.

Quick Tip to Solve: For separated lenses, first locate the intermediate image on the common axis; measure its distance from the second lens before applying the lens formula again.

20. A light of wavelength 400 nm is incident on metal surface whose work function is 3.0×10^{-19} J. Calculate the speed of the fastest photoelectrons emitted. [2 marks]

Solution:

Concept:

- A photon of wavelength λ has energy $E_\gamma = hc/\lambda$, where h is Planck's constant and c is the speed of light in vacuum.
- Einstein's photoelectric equation is $K_{\max} = hc/\lambda - \phi$, where ϕ is the work function. For an electron of mass m_e , $K_{\max} = \frac{1}{2}m_e v_{\max}^2$.

Step 1: Calculate the incident photon energy Convert the wavelength to SI units: $400 \text{ nm} = 4.00 \times 10^{-7} \text{ m}$. Using $h = 6.63 \times 10^{-34} \text{ J s}$ and $c = 3.00 \times 10^8 \text{ m s}^{-1}$,

$$E_\gamma = \frac{(6.63 \times 10^{-34})(3.00 \times 10^8)}{4.00 \times 10^{-7}} = 4.9725 \times 10^{-19} \text{ J}.$$

This exceeds the given work function, so photoelectron emission is possible.

Step 2: Find the maximum kinetic energy and speed The fastest electron retains all the photon energy remaining after the work function has been supplied. Hence

$$K_{\max} = (4.9725 - 3.0) \times 10^{-19} = 1.9725 \times 10^{-19} \text{ J}.$$

Substituting $m_e = 9.1 \times 10^{-31} \text{ kg}$ gives

$$v_{\max} = \sqrt{\frac{2K_{\max}}{m_e}} = \sqrt{\frac{2(1.9725 \times 10^{-19})}{9.1 \times 10^{-31}}} = \sqrt{4.335 \times 10^{11}} \text{ m s}^{-1}.$$

The energy used to release the electron must be subtracted before converting the remaining energy into its speed.

Step 3: Conclusion The speed of the fastest emitted photoelectrons is approximately $6.6 \times 10^5 \text{ m s}^{-1}$.

Quick Tip to Solve: Convert nanometres to metres, subtract the work function from hc/λ , and only then take $\sqrt{2K_{\max}/m_e}$.

21. The threshold voltage of a silicon diode is 0.7 V. It is operated at this point by connecting the diode in series with a battery of V volt and a resistor of $1000\ \Omega$. Find the value of V when the current drawn is 15 mA. [2 marks]

Solution:

Concept:

- A forward-biased silicon diode has an approximately 0.7 V potential drop at the stated operating point. This diode drop must be included in the total applied voltage.
- Kirchhoff's loop rule gives $V = V_D + IR$ for the series circuit, where V is the battery voltage, V_D is the diode drop, I is the common series current and R is the resistor's resistance.

Step 1: Calculate the potential difference across the resistor Because the diode and resistor are in series, the given current $15\text{ mA} = 15 \times 10^{-3}\text{ A}$ flows through the $1000\ \Omega$ resistor. By Ohm's law,

$$V_R = IR = (15 \times 10^{-3})(1000) = 15\text{ V}.$$

This is the resistor's voltage drop alone; the source must also provide the voltage across the conducting diode.

Step 2: Apply Kirchhoff's loop rule Take a loop in the direction of current. The battery produces a potential rise, while the resistor and forward-biased diode produce potential drops. Therefore

$$V - IR - V_D = 0, \quad V = 15 + 0.7\text{ V}.$$

The battery is connected with its positive terminal towards the diode's p-side so that the diode is forward biased. A battery supplying only the resistor drop would leave out the stated diode threshold voltage.

Step 3: Conclusion The required battery voltage is $V = 15.7\text{ V}$, with the diode connected in forward bias.

Quick Tip to Solve: In a series diode circuit, first find IR and then add the silicon diode's 0.7 V forward drop to obtain the battery voltage.

Section C (21 marks)

22. (a) A cell of e.m.f. E and internal resistance r is connected with a variable external resistance R and a voltmeter showing potential drop V across R . Obtain the relationship between V , E , R and r .
(b) Draw the shape of the graph showing the variation of terminal voltage V of the cell as a function of current I drawn from it. How one can determine the e.m.f. of the cell and its internal resistance from this graph? [3 marks]

Solution:

Concept:

- A cell of emf E and internal resistance r supplies current through the total resistance $R + r$. The voltmeter is taken to have very high resistance, so its current is negligible.
- The terminal voltage V equals the voltage across the external resistance: $V = IR$. For a discharging cell, Kirchhoff's loop rule gives $E = V + Ir$, where Ir is the internal voltage drop.

Step 1: (a) Relate terminal voltage to the resistances The same current flows through the cell's

internal resistance and the external load. Applying Ohm's law to the complete circuit,

$$I = \frac{E}{R + r}.$$

The voltmeter measures the potential difference across R , rather than the emf directly. Therefore

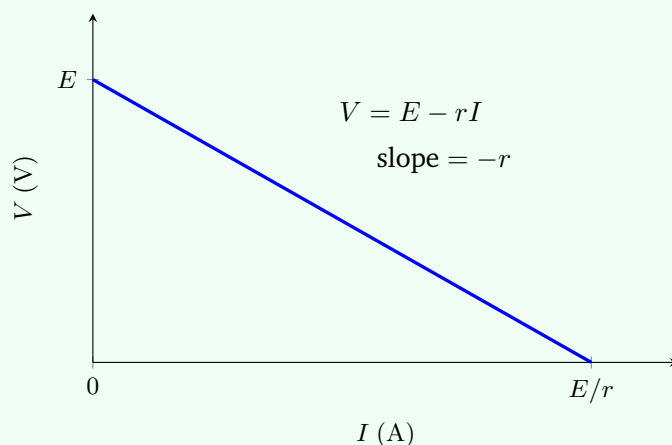
$$V = IR = \frac{ER}{R + r}.$$

Equivalently, $V = E - Ir$. For a nonzero current through a cell with positive internal resistance, the terminal voltage is less than the emf because some potential is lost internally.

Step 2: (b) Plot terminal voltage against current Keep E and r constant and vary R to change the current. Rearrange the loop equation as

$$V = E - rI.$$

This has the straight-line form $y = c + mx$: put I on the horizontal axis and V on the vertical axis. The line slopes downwards, starting at $V = E$ when $I = 0$. Its extension reaches $V = 0$ at $I = E/r$, the idealised short-circuit current.



Terminal voltage decreases linearly with current; the intercept is E and the slope is $-r$.

Step 3: Determine emf and internal resistance from the line Read the voltage-axis intercept, where no current is drawn: it gives the cell's emf E . For two points (I_1, V_1) and (I_2, V_2) on the fitted line with $I_2 > I_1$,

$$\text{slope} = \frac{V_2 - V_1}{I_2 - I_1} = -r, \quad r = \frac{V_1 - V_2}{I_2 - I_1}.$$

Thus the internal resistance is the magnitude of the negative slope, in $\text{V/A} = \Omega$. It is calculated from coordinate differences, not from the apparent angle of the line on an arbitrarily scaled graph.

Step 4: Conclusion The required relation is $V = ER/(R + r) = E - Ir$. The V -versus- I graph is a descending straight line: its voltage-axis intercept gives E , and the magnitude of its slope gives r .

Quick Tip to Solve: Write $V = E - rI$ before drawing the graph: the constant term gives the vertical intercept and the coefficient of current gives the negative slope.

23(a). In a region of a uniform electric field $\vec{E}$, a negatively charged particle is moving with a constant velocity $\vec{v} = -v_o \hat{i}$ near a long straight conductor coinciding with XX' axis and carrying current I towards $-X$ axis. The particle remains at a distance d from the conductor.

(i) Draw diagram showing direction of electric and magnetic fields.

(ii) What are the various forces acting on the charged particle?

(iii) Find the value of v_o in terms of E , d and I .

[3 marks]

Solution:

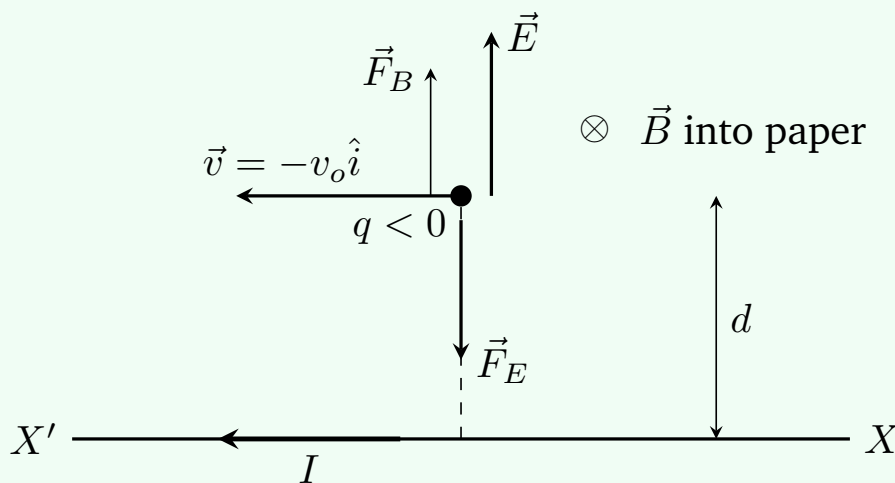
Concept:

- At perpendicular distance d from a long straight wire carrying current I , the magnetic field has magnitude $B = \mu_0 I / (2\pi d)$. Its direction follows the right-hand thumb rule.
- The electric and magnetic forces are $\vec{F}_E = q\vec{E}$ and $\vec{F}_B = q(\vec{v} \times \vec{B})$. Both directions reverse when the charge is negative.
- Constant velocity requires zero net force. In perpendicular electric and magnetic fields this gives $E = v_o B$, where v_o is the particle's speed.

Step 1: (i) Draw and identify the field directions Choose the particle above the wire, at $y = d$, and take $+\hat{k}$ out of the paper. Both the current and the particle velocity point along $-\hat{i}$. Curling the right-hand fingers around the wire gives a magnetic field into the paper at the particle:

$$\vec{B} = -\frac{\mu_0 I}{2\pi d} \hat{k}.$$

The electric field must point upward, away from the wire, so that the electric force on the negative charge is downward. The figure shows this choice of side; for a particle below the wire both field directions reverse.



Fields and forces for a negative charge above the current-carrying wire.

Step 2: (ii) Determine the forces on the negative charge Write $q = -|q|$ and $\vec{v} = -v_o \hat{i}$. Since $\hat{i} \times \hat{k} = -\hat{j}$,

$$\vec{F}_B = (-|q|)[(-v_o \hat{i}) \times (-B \hat{k})] = |q|v_o B \hat{j}.$$

Thus the magnetic force is away from the wire. The electric force is $\vec{F}_E = -|q|E\hat{j}$, towards the wire. These two electromagnetic forces are equal and opposite, consistent with the stated constant velocity and fixed distance from the conductor.

Step 3: (iii) Balance the electric and magnetic forces Since $\vec{E}$, $\vec{B}$ and $\vec{v}$ are mutually perpendicular,

the magnetic-force magnitude is $|q|v_oB$. Set the net transverse force equal to zero and substitute the wire's field:

$$\begin{aligned}|q|E &= |q|v_oB, \\ E &= v_o \frac{\mu_0 I}{2\pi d}, \\ v_o &= \frac{2\pi dE}{\mu_0 I}.\end{aligned}$$

The charge magnitude cancels, so the required speed depends on the field strengths rather than on the charge or mass of the particle.

Step 4: Conclusion For the particle drawn above the wire, $\vec{B}$ is into the paper and $\vec{E}$ is upward. The magnetic force is away from the wire and the electric force is towards it. Their balance requires $v_o = 2\pi dE/(\mu_0 I)$, with velocity $\vec{v} = -v_o \hat{i}$.

Quick Tip to Solve: First find $\vec{v} \times \vec{B}$, then reverse it for the negative charge. Balance force magnitudes only after checking that their directions oppose.

OR

23(b). Two infinitely long conductors kept along XX' and YY' axes are carrying current I_1 and I_2 along $-X$ axis and $-Y$ axis respectively. Find the magnitude and direction of the net magnetic field produced at point $P(X, Y)$. [3 marks]

Solution:

Concept:

- An infinitely long straight wire produces $B = \mu_0 I / (2\pi r)$ at perpendicular distance r . The field circles the wire with direction given by the right-hand thumb rule.
- Magnetic fields obey vector superposition: $\vec{B}_{\text{net}} = \vec{B}_1 + \vec{B}_2$. Fields normal to the same plane are added algebraically after assigning signs.

Step 1: Find the field due to the conductor on the X axis Take $+\hat{k}$ perpendicular to the XY plane and out of the paper. At a point $P(X, Y)$ in the first quadrant, the perpendicular distance from the X-axis conductor is Y . Its current is along $-\hat{i}$. The right-hand thumb rule therefore gives a field into the paper:

$$\vec{B}_1 = -\frac{\mu_0 I_1}{2\pi Y} \hat{k}.$$

In particular, the distance used is Y , not the distance $\sqrt{X^2 + Y^2}$ from the origin, because the wire is infinitely long.

Step 2: Find the field due to the conductor on the Y axis The distance from the Y-axis conductor is X , and its current points along $-\hat{j}$. At the point to its right, the field points out of the paper, since $(-\hat{j}) \times \hat{i} = +\hat{k}$. Hence

$$\vec{B}_2 = +\frac{\mu_0 I_2}{2\pi X} \hat{k}.$$

Thus, for positive X, Y , the two contributions oppose even though the wires themselves are perpendicular.

Step 3: Superpose the two perpendicular-to-plane fields Add the signed components along $\hat{k}$:

$$\vec{B}_{\text{net}} = \frac{\mu_0}{2\pi} \left(\frac{I_2}{X} - \frac{I_1}{Y} \right) \hat{k}.$$

If $I_2/X > I_1/Y$, the field is out of the paper. If $I_2/X < I_1/Y$, it is into the paper. If the two ratios are equal, the resultant is zero and has no direction. The same signed-coordinate vector expression also applies in other quadrants, with nonzero X and Y ; changing a coordinate's sign automatically reverses the corresponding field.

Step 4: Conclusion The net field has magnitude $B_{\text{net}} = \frac{\mu_0}{2\pi} \left| \frac{I_2}{X} - \frac{I_1}{Y} \right|$. Its direction is normal to the XY plane: outwards for a positive bracket, inwards for a negative bracket, and zero when the bracket vanishes.

Quick Tip to Solve: Pair the X -axis wire with distance Y and the Y -axis wire with distance X ; decide into/out of the paper before adding their fields.

24. (a) State Lenz's law.

(b) In the given figure:

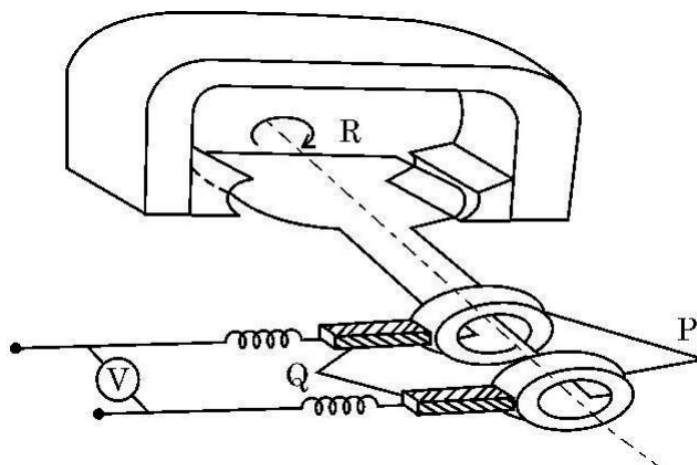
(i) Identify the machine.

(ii) Name the parts P and Q and R of the machine.

(iii) Give the polarities of the magnetic poles.

(iv) Write the two ways of increasing the output voltage.

[3 marks]



Solution:

Concept:

- Faraday's law gives the induced emf as $\mathcal{E} = -d(N\Phi_B)/dt$, where $N\Phi_B$ is the magnetic flux linkage. The minus sign expresses Lenz's law.
- For a coil of N turns and area A , rotating with angular speed ω in a uniform magnetic field B , the peak generated emf is $\mathcal{E}_0 = NBA\omega$.

Step 1: (a) State Lenz's law Lenz's law states that the induced current flows in such a direction that the magnetic effect produced by it opposes the change in magnetic flux which causes it. It opposes the change of flux, not necessarily the existing magnetic field. This opposition explains why mechanical

work must be supplied to keep a generator rotating while it delivers electrical energy.

Step 2: (b)(i) Identify the machine The machine is an **alternating-current generator**, or alternator. The armature rotates between magnetic poles, changing its flux linkage. The induced emf reverses after each half-turn. Two separate complete slip rings maintain electrical contact with the rotating coil, so the external output is alternating.

Step 3: (b)(ii) Name the labelled parts P denotes the **two slip rings**, each connected to one end of the rotating coil. Q denotes the **carbon brushes**, which stay stationary and collect the output through sliding contact with the rings. R denotes the **armature coil**, which rotates in the magnetic field and develops the induced emf. The two complete rings are the feature that identifies this as an AC generator.

Step 4: (b)(iii) Specify the magnetic poles The conventional pole assignment is **left pole N and right pole S**, giving a magnetic field across the gap from left to right. The printed sketch gives the rotation direction but no definite induced-current direction or output polarity. Thus the absolute pole assignment is not uniquely fixed by the drawing alone: interchanging N and S reverses the instantaneous emf while the machine still operates as an AC generator.

Step 5: (b)(iv) Increase the output voltage Two ways are: **increase the armature's angular speed** ω , and **increase the magnetic-field strength** B , for example by using stronger magnetic poles. Since

$$\mathcal{E}_0 = NBA\omega,$$

either change increases the peak output voltage with the other quantities fixed. The rms output voltage increases in the same proportion because $\mathcal{E}_{\text{rms}} = \mathcal{E}_0/\sqrt{2}$.

Step 6: Conclusion Lenz's law opposes the flux change causing induction. The machine is an AC generator: P = slip rings, Q = carbon brushes, and R = armature coil. A conventional assignment is left N and right S. Faster rotation or a stronger magnetic field increases the output voltage.

Quick Tip to Solve: Identify the two complete slip rings first; then use $\mathcal{E}_0 = NBA\omega$ to select two independent ways to raise the generated voltage.

25. (a) The electric field $\vec{E}$ of an electromagnetic wave propagating in north direction is oscillating in up and down direction. Describe the direction of magnetic field $\vec{B}$ of the wave.

(b) Are the wave length of radio waves and microwaves longer or shorter than those detectable by human eyes?

(c) Write main use of each of the following in human life:

(i) Infrared waves (ii) Gamma rays

[3 marks]

Solution:

Concept:

- An electromagnetic wave is transverse: its electric field $\vec{E}$, magnetic field $\vec{B}$, and propagation direction are mutually perpendicular. Energy travels in the direction of $\vec{E} \times \vec{B}$.
- In the electromagnetic spectrum, radio waves and microwaves have lower frequencies and longer wavelengths than visible light; in vacuum $c = \nu\lambda$, where ν is frequency and λ is wavelength.
- The uses of electromagnetic radiation depend on its interaction with matter: infrared radiation produces heating, while highly penetrating gamma rays can destroy living cells.

Step 1: (a) Apply the perpendicular-field rule The propagation direction is north and the electric field oscillates vertically. The magnetic field must therefore oscillate horizontally along the east-west direction. Its instantaneous sense is fixed by the right-hand rule: when $\vec{E}$ points upward, $\vec{B}$ points east, so that $\vec{E} \times \vec{B}$ points north. When the electric field points downward, the magnetic field points west. Both fields reverse together, leaving the propagation direction unchanged.

Step 2: (b) Compare the wavelengths with visible light The human eye detects visible light, approximately in the wavelength range 400–700 nm. Moving from visible light towards infrared, microwaves and radio waves, the wavelength increases. Consequently, both radio waves and microwaves have wavelengths longer than those detectable by human eyes. Radio wavelengths are generally longer than microwave wavelengths as well.

Step 3: (c) Relate each radiation to a practical use (i) Infrared waves are used in physiotherapy to provide controlled heating of body tissues and relief from muscular discomfort. Their heating effect is the relevant property.

(ii) Gamma rays are used in radiotherapy to destroy cancerous cells. Their high photon energy and penetrating power allow them to reach and damage the targeted tissue.

Step 4: Conclusion (a) The magnetic field oscillates east-west, with $\vec{E} \times \vec{B}$ directed north. (b) Both radio and microwave wavelengths are longer than visible wavelengths. (c) Infrared: physiotherapy heating; gamma rays: cancer radiotherapy.

Quick Tip to Solve: Use the right-hand rule for $\vec{E} \times \vec{B}$, then recall the wavelength order: radio, microwave, infrared, visible, ultraviolet, X-ray, gamma ray.

26. (a) When a parallel beam of light enters water surface obliquely at some angle, what is the effect on the width of the beam?

(b) With the help of a ray diagram, show that a straw appears bent when it is partly dipped in water and explain it.

(c) Explain the transmission of optical signal through an optical fibre by a diagram. [3 marks]

Solution:

Concept:

- Snell's law is $n_1 \sin i = n_2 \sin r$, where the angles are measured from the normal. Light entering water from air bends towards the normal, so $r < i$.
- Light emerging from water into air bends away from the normal. The eye traces the emerging rays backwards along straight lines and sees a virtual image at a smaller depth.
- Total internal reflection requires travel from higher to lower refractive index and an incidence angle greater than the critical angle. At a fibre boundary, $\sin i_c = n_{\text{clad}}/n_{\text{core}}$.

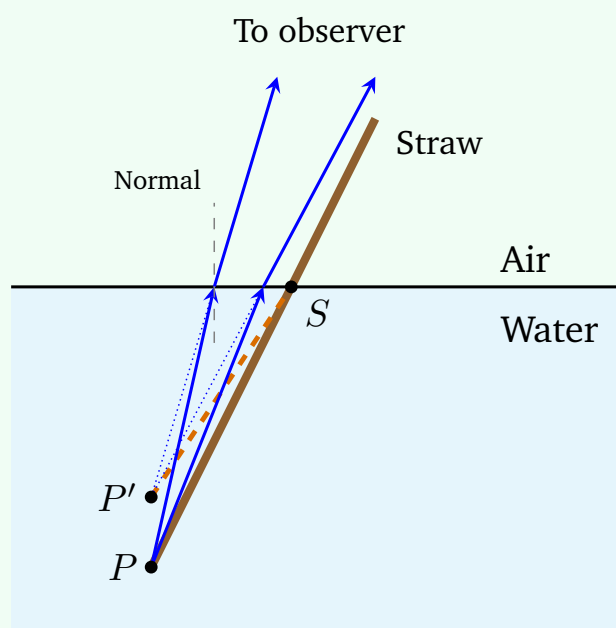
Step 1: (a) Compare the perpendicular beam widths Let the two extreme rays meet the water surface at points separated by L . The incident beam width, measured perpendicular to its rays, is $w = L \cos i$,

whereas the refracted beam width is $w' = L \cos r$. Thus

$$\frac{w'}{w} = \frac{\cos r}{\cos i} > 1,$$

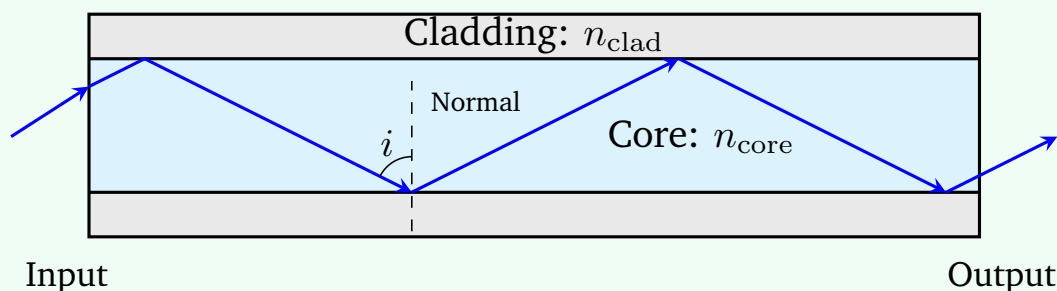
since refraction into water gives $r < i$. Therefore, the width of the beam increases. The surface footprint L is common to both beams; it must not be confused with the perpendicular beam width.

Step 2: (b) Trace rays from the submerged straw In the diagram, P is a point on the submerged straw and S is where the straw meets the surface. Rays from P refract away from the normal on emerging into air. Their dotted backward extensions meet at the virtual image P' , closer to the surface. For viewing close to the normal, apparent depth is approximately real depth divided by the refractive index of water relative to air. The submerged portion therefore appears raised, along SP' , while the portion in air is seen directly. This change of apparent direction at S makes the straw look bent.



Refraction at water-air surface: solid blue rays reach the observer; dotted extensions locate the raised virtual image P' . The sketch represents near-normal viewing.

Step 3: (c) Follow the light through the fibre An optical fibre has a transparent core surrounded by cladding with $n_{\text{core}} > n_{\text{clad}}$. Light admitted within the acceptance angle strikes the core-cladding boundary at an angle $i > i_c$, measured from the normal. It undergoes repeated total internal reflection at the successive boundaries and remains confined to the core. A sequence of light pulses carrying information can consequently travel along the fibre with small loss, emerging at the other end as an optical signal.



Repeated total internal reflection confines light to the core, where $n_{\text{core}} > n_{\text{clad}}$ and every boundary incidence satisfies $i > i_c$.

Step 4: Conclusion (a) The beam widens on entering water obliquely. (b) Refraction raises the apparent position of the submerged straw, making it appear bent. (c) Repeated total internal reflection in the denser core transmits the optical signal.

Quick Tip to Solve: Define beam width perpendicular to the rays. For fibres, always state both conditions: denser core and incidence angle above the critical angle.

27. (a) Show the variation of binding energy per nucleon with mass number. Write the significance of the binding energy curve.

(b) Two nuclei with lower binding energy per nucleon form a nuclei with more binding energy per nucleon.

(i) What type of nuclear reaction is it?

(ii) Whether the total mass of nuclei increases, decreases or remains unchanged?

(iii) Does the process require energy or produce energy?

[3 marks]

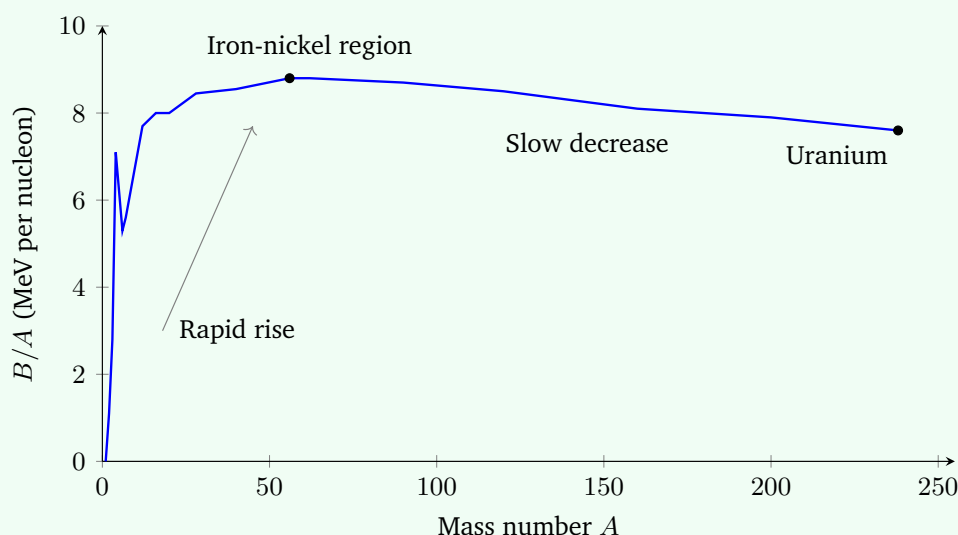
Solution:

Concept:

- Binding energy B is the energy required to separate a nucleus into its constituent protons and neutrons. The average binding energy per nucleon is B/A , where A is the mass number.
- Larger B/A means that the nucleons are more tightly bound and indicates greater nuclear stability. The nuclear mass is less than the total free-nucleon mass by the mass defect B/c^2 .
- A nuclear process releases energy when the final total binding energy exceeds the initial total binding energy: $Q = B_f - B_i = (M_i - M_f)c^2$, where M_i and M_f are the initial and final total rest masses.

Step 1: (a) Sketch and interpret the binding-energy curve Plot B/A , in MeV per nucleon, against mass number A . The curve rises rapidly, with irregularities, for light nuclei. It reaches a broad maximum of about 8.8 MeV per nucleon in the iron-nickel region, near $A \simeq 56-62$, and then decreases slowly towards heavy nuclei; for uranium it is approximately 7.6 MeV per nucleon.

The high middle portion shows that medium-mass nuclei are particularly stable. The curve explains why fusion of suitable light nuclei and fission of suitable heavy nuclei can both release energy: in each case the products lie closer to the region of greater binding energy per nucleon. The nearly flat middle region also reflects the short-range, saturating nature of nuclear forces.



Schematic binding energy per nucleon versus mass number; the broad maximum lies in the iron-nickel region.

Step 2: (b)(i) Identify the nuclear process Two initially separate nuclei combine to form a single nucleus. This joining process is nuclear fusion. In the situation stated, the product has greater binding energy per nucleon than the original nuclei and is therefore more tightly bound.

Step 3: (b)(ii)–(iii) Relate binding energy to mass and energy The total number of nucleons is conserved. Hence the stated increase in binding energy per nucleon means that the total binding energy increases. A larger binding energy corresponds to a larger mass defect, so the final nuclear rest mass is smaller than the sum of the initial nuclear rest masses:

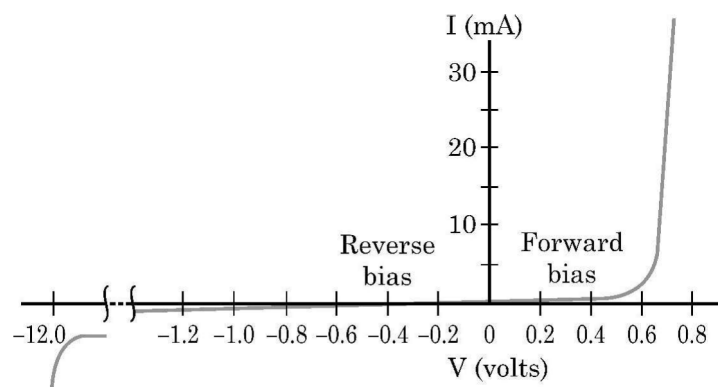
$$\Delta B = B_f - B_i > 0, \quad M_i - M_f = \frac{\Delta B}{c^2} > 0.$$

The reduction in rest mass appears as released energy, $Q = \Delta B$. Thus the process produces energy overall. Energy may initially be needed to overcome the repulsion between the positively charged nuclei, but this does not change the positive net energy release specified here.

Step 4: Conclusion (a) Binding energy per nucleon peaks near the iron-nickel region; a larger value indicates greater binding and stability. (b) The process is nuclear fusion, the total nuclear rest mass decreases, and energy is released.

Quick Tip to Solve: For a proposed reaction, compare total binding energies: a gain in binding energy means a loss of rest mass and a release of energy, even if initiation needs energy.

28. (a) What are majority and minority charge carriers in an extrinsic semiconductor?
- (b) A p-n junction is forward biased. Describe the movement of the charge carriers which produce current in it.
- (c) The graph shows the variation of current with voltage for a p-n junction diode. Estimate the dynamic resistance of diode at $V = -0.6$ volt. [3 marks]



Solution:

Concept:

- Doping produces an extrinsic semiconductor. The carriers present in greater concentration are majority carriers, whereas those present in smaller concentration are minority carriers.
- Forward bias reduces the junction potential barrier and narrows the depletion layer, allowing majority carriers to diffuse across the junction.
- Dynamic resistance at an operating point is the reciprocal slope of the current-voltage curve:

$$r_d = \frac{dV}{dI}, \text{ estimated using nearby changes as } \Delta V / \Delta I.$$

Step 1: Identify the carriers in each semiconductor (a) In an n-type semiconductor, donor impurities supply many free electrons: electrons are the majority carriers and holes are the minority carriers. In a p-type semiconductor, acceptor impurities produce many holes: holes are the majority carriers and electrons are the minority carriers. The terms describe relative concentrations, not the sign of the semiconductor's net charge; the semiconductor remains electrically neutral overall.

Step 2: Trace the forward current across the junction (b) Connect the p-side to the positive terminal and the n-side to the negative terminal of the source. The reduced barrier allows holes to move from p to n and electrons to move from n to p. These injected carriers recombine with opposite carriers after crossing the junction, while the source continually supplies carriers. Electron motion from n to p produces conventional current from p to n, so electron and hole motions contribute to conventional current in the same direction across the junction.

Step 3: Read the local slope in reverse bias (c) The operating voltage $V = -0.6$ V is on the nearly horizontal reverse-bias branch, well before breakdown. A small change in reverse voltage produces essentially no visible change in reverse current on the given graph. Therefore

$$r_d = \frac{\Delta V}{\Delta I}, \quad \Delta I \simeq 0.$$

Its reciprocal slope is consequently extremely large. In the idealised horizontal-branch approximation used to read this graph, the dynamic resistance tends to infinity. This is a local slope calculation; the ratio V/I would instead be the static resistance and is not asked for.

Step 4: Conclusion In n-type material the majority/minority carriers are electrons/holes; in p-type

material they are holes/electrons. Under forward bias, electrons cross from n to p and holes from p to n. At -0.6 V , the dynamic resistance is very high, ideally $r_d \rightarrow \infty$.

Quick Tip to Solve: For dynamic resistance, inspect the slope near the stated voltage: a horizontal reverse-current branch means a nearly infinite reciprocal slope.

Section D (8 marks)

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

29. A parallel plate capacitor has two parallel plates which are separated by an insulating medium like air, mica, etc. When the plates are connected to the terminals of a battery, they get equal and opposite charges and an electric field is set up in between them. This electric field between the two plates depends upon the potential difference applied, the separation of the plates and nature of the medium between the plates. [4 marks]

29(i). The electric field between the plates of a parallel plate capacitor is E . Now the separation between the plates is doubled and simultaneously the applied potential difference between the plates is reduced to half of its initial value. The new value of the electric field between the plates will be: [1 mark]

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

Correct Answer: (C) $\frac{E}{4}$

Solution:

Concept:

- Between ideal parallel capacitor plates, the uniform electric-field magnitude is $E = V/d$, where V is the potential difference and d is the separation.
- When both voltage and separation change, take their ratio together: $E'/E = (V'/V)/(d'/d)$.

Step 1: Substitute both changes The new voltage is $V' = V/2$, and the new separation is $d' = 2d$. Hence

$$E' = \frac{V'}{d'} = \frac{V/2}{2d} = \frac{V}{4d}.$$

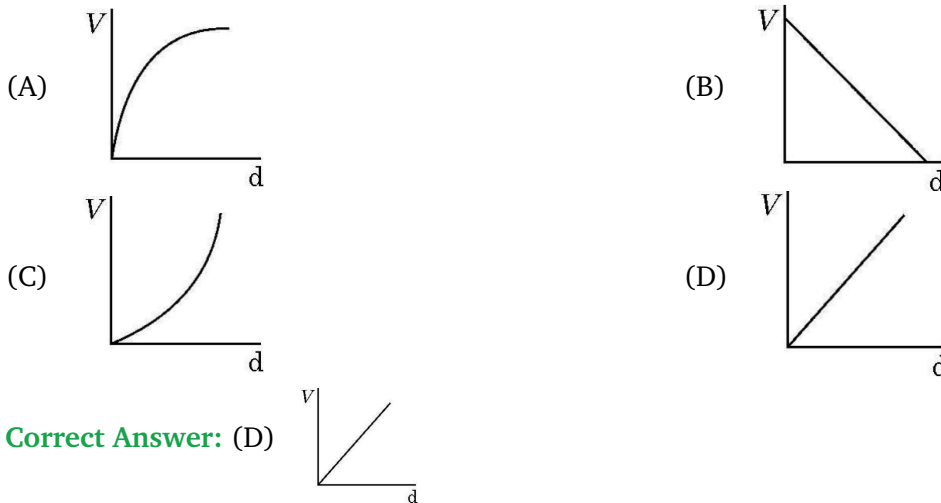
Halving the numerator and doubling the denominator each reduce the field by a factor of two.

Step 2: Compare the four choices Since initially $V/d = E$, the combined reduction factor is four. Option (A) would require the voltage and separation to change by the same factor. Option (B) increases the field although both stated changes reduce it. Option (D) accounts for only one of the two changes.

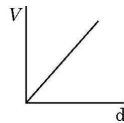
Step 3: Conclusion The new field is $E' = E/4$. Hence, the correct option is (C).

Quick Tip to Solve: Write the field ratio as voltage factor divided by separation factor: here $(1/2)/2 = 1/4$.

29(ii). A constant electric field is to be maintained between the two plates of a capacitor whose separation d changes with time. Which of the graphs correctly depict the potential difference (V) to be applied between the plates as a function of separation between the plates (d) to maintain the constant electric field? [1 mark]



Correct Answer: (D)



Solution:

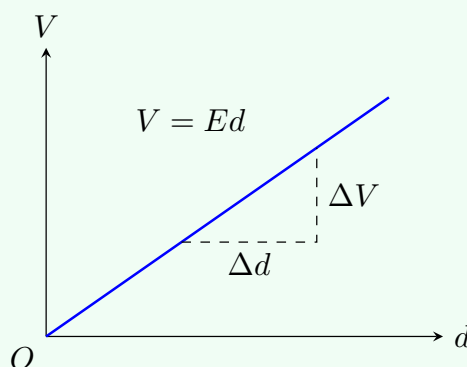
Concept:

- For an ideal parallel-plate capacitor, the field magnitude is $E = V/d$, where d is plate separation and V is the applied potential difference.
- At fixed E , the voltage obeys $V = Ed$. Thus the slope of the V -against- d graph is the positive constant E .

Step 1: Rearrange the field relation To preserve the same electric field while the separation changes, the applied voltage must satisfy

$$V(d) = Ed.$$

Therefore doubling the separation requires doubling the voltage. The mathematical relation is a straight line through the origin, even though physical plates cannot occupy the limiting zero-separation position.



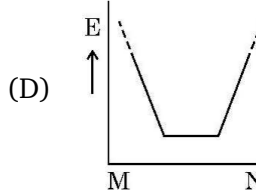
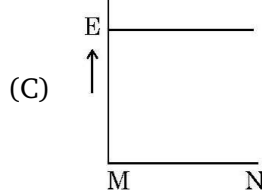
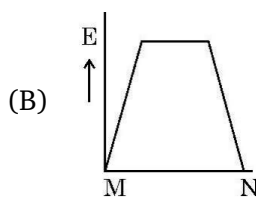
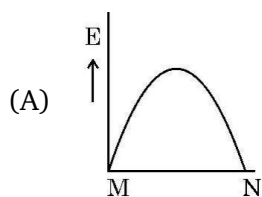
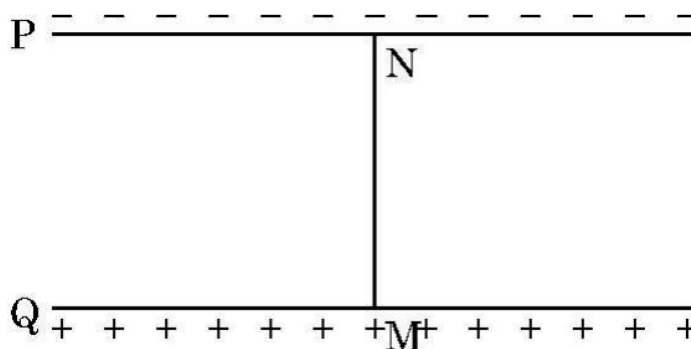
Voltage increases linearly with separation; the slope equals the fixed field.

Step 2: Identify the constant-slope graph Option (D) has a positive constant slope and passes through the origin. The curved graphs in (A) and (C) make V/d vary with separation. Option (B) decreases voltage as separation grows and therefore cannot maintain a positive constant V/d .

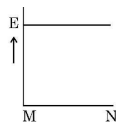
Step 3: Conclusion The required graph is the rising straight line through the origin, $V = Ed$. Hence, the correct option is (D).

Quick Tip to Solve: Rearrange the required constant into the plotted variables: constant $E = V/d$ means a straight line $V = Ed$ through the origin.

29(iii). In the above figure P, Q are the two parallel plates of a capacitor. Plate Q is at positive potential with respect to plate P. MN is an imaginary line drawn perpendicular to the plates. Which of the graphs shows correctly the variations of the magnitude of electric field strength E along the line MN? [1 mark]



Correct Answer: (C)



Solution:

Concept:

- Neglecting edge effects, the electric field between two parallel oppositely charged plates is uniform: $E = \sigma/\epsilon$, where σ is the surface charge density and ϵ the medium's permittivity.
- Electric field points from the positive plate towards the negative plate, and from higher to lower potential. Its magnitude is independent of position inside the gap.

Step 1: Locate the path inside the capacitor In the printed figure, M is on the lower positive plate Q and N is on the upper negative plate P. The line MN crosses the inter-plate space perpendicularly. Since Q is at higher potential, the electric field points from Q towards P, along MN.

Step 2: Compare the magnitude graphs The magnitude remains the same at every point in the gap. Thus its graph against position along MN is a horizontal line at a nonzero value. Option (A) changes continuously to a maximum; option (B) adds rising and falling intervals; option (D) contains a central minimum. These variations do not describe the uniform field between ideal parallel plates. Edge effects are neglected, as in the standard capacitor model.

Step 3: Conclusion The field magnitude is constant between M and N, as shown by the horizontal graph. Hence, the correct option is (C).

Quick Tip to Solve: First locate M and N: both bound the plate gap, so use the uniform interior field, not a graph extending outside the capacitor.

29(iv). Three parallel plates are placed above each other with equal displacement $\vec{d}$ between neighbouring plates. The electric field between the first pair of the plates is $\vec{E}_1$ and the electric field between the second pair of the plates is $\vec{E}_2$. The potential difference between the third and the first plate is – [1 mark]

(A) $(\vec{E}_1 + \vec{E}_2) \cdot \vec{d}$

(B) $(\vec{E}_1 - \vec{E}_2) \cdot \vec{d}$

(C) $(\vec{E}_2 - \vec{E}_1) \cdot \vec{d}$

(D) $\frac{d(E_1 + E_2)}{2}$

Correct Answer: (A) $(\vec{E}_1 + \vec{E}_2) \cdot \vec{d}$

Solution:

Concept:

- The signed potential change is $V_B - V_A = - \int_A^B \vec{E} \cdot d\vec{l}$. In a uniform field, this becomes $-\vec{E} \cdot (\vec{r}_B - \vec{r}_A)$.
- Potential differences across consecutive gaps add algebraically. Each field acts across one complete gap of separation d , so the two contributions must be added, not averaged.

Step 1: Specify the displacement convention The printed wording gives the displacement between neighbouring plates without an arrow diagram fixing its orientation. To express $V_3 - V_1$, take $\vec{d}$ from plate 3 to plate 2 and from plate 2 to plate 1. Integration in that direction gives

$$V_2 - V_3 = -\vec{E}_2 \cdot \vec{d},$$

$$V_1 - V_2 = -\vec{E}_1 \cdot \vec{d}.$$

This convention makes the endpoint order and the sign explicit.

Step 2: Add the two gap contributions Adding and reversing the endpoint order yields

$$V_3 - V_1 = (\vec{E}_1 + \vec{E}_2) \cdot \vec{d}.$$

Options (B) and (C) incorrectly subtract one gap contribution. Option (D) incorrectly divides the total by two: the two gaps are in succession, so their voltage differences add. If instead $\vec{d}$ is defined

from plate 1 towards plate 3, the signed $V_3 - V_1$ carries an overall minus sign; the sum in (A) then represents $V_1 - V_3$. The printed choices use the additive voltage-difference convention.

Step 3: Conclusion The intended potential-difference expression is $(\vec{E}_1 + \vec{E}_2) \cdot \vec{d}$, with the displacement and endpoint convention specified above. Hence, the correct option is (A).

Quick Tip to Solve: Add the two gap voltages, each over distance d ; use $V_B - V_A = -\int_A^B \vec{E} \cdot d\vec{l}$ to fix the overall sign before choosing endpoints.

OR

29(iv). A material of dielectric constant K is filled in a parallel plate capacitor of capacitance C . The new value of its capacitance becomes [1 mark]

- (A) C
- (B) $\frac{C}{K}$
- (C) CK
- (D) $C \left(1 + \frac{1}{K}\right)$

Correct Answer: (C) CK

Solution:

Concept:

- The capacitance of an air-filled parallel-plate capacitor is $C = \epsilon_0 A/d$, where A is the plate area and d is their separation.
- A dielectric completely filling the gap changes the permittivity to $\epsilon = K\epsilon_0$, where the dielectric constant K is dimensionless.

Step 1: Replace the permittivity The plate geometry remains the same when the material is inserted. With the gap completely filled by dielectric,

$$C' = \frac{K\epsilon_0 A}{d}.$$

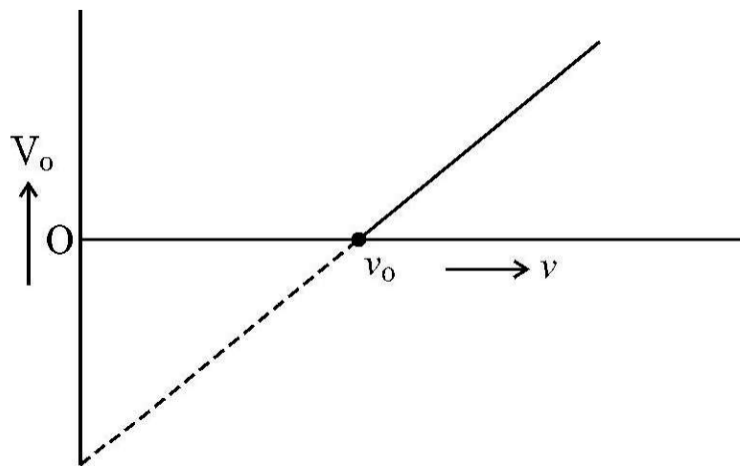
Comparing this with the original expression $C = \epsilon_0 A/d$ shows that the capacitance increases in the ratio K .

Step 2: Check the alternatives Option (A) would apply only when $K = 1$, not for a general dielectric. Option (B) incorrectly decreases capacitance by a factor K . Option (D) does not follow from replacing the permittivity and even predicts $2C$ when $K = 1$, when there should be no change. Capacitance is determined by geometry and medium, so this result does not depend on whether the battery stays connected.

Step 3: Conclusion The new capacitance is $C' = KC$. Hence, the correct option is (C).

Quick Tip to Solve: For a dielectric that fills the entire gap, multiply the original capacitance by K ; verify the formula returns C when $K = 1$.

30. When a photon of suitable frequency is incident on a metal surface, photoelectron is emitted from it. If the frequency is below a threshold frequency ν_0 for the surface, no photoelectron is emitted. For a photon of frequency ν ($\nu > \nu_0$), the kinetic energy of the emitted photoelectrons is $h(\nu - \nu_0)$. The photocurrent can be stopped by applying a potential V_0 , called 'stopping potential' on the anode. Thus maximum kinetic energy of photoelectrons $K_m = eV_0 = h(\nu - \nu_0)$. The experimental graph between V_0 and ν for a metal is shown in figure. This is a straight line of slope m . [4 marks]



30(i). The straight line graphs obtained for two metals

[1 mark]

- (A) coincide each other.
- (B) are parallel to each other.
- (C) are not parallel to each other and cross at a point on ν -axis.
- (D) are not parallel to each other and do not cross at a point on ν -axis.

Correct Answer: (B) are parallel to each other.

Solution:

Concept:

- Einstein's photoelectric equation is $eV_0 = h\nu - \phi$, where V_0 is the stopping-potential magnitude, ν is incident frequency, and ϕ is the metal's work function.
- A graph of V_0 against ν has slope h/e . Planck's constant h and elementary charge e are universal constants.

Step 1: Compare the slopes For either metal, divide Einstein's equation by e to obtain

$$V_0 = \frac{h}{e}\nu - \frac{\phi}{e}.$$

The coefficient of frequency is the same for both metals, so their straight lines have the same slope regardless of their different work functions.

Step 2: Compare the intercepts and alternatives Different work functions give different vertical intercepts $-\phi/e$ and different threshold frequencies ϕ/h . Thus the ordinary two-metal graphs are displaced parallel lines. Coincidence would require equal work functions and is not the general result.

Options (C) and (D) incorrectly require different slopes and crossing or nonparallel lines.

Step 3: Conclusion The straight lines for two metals are parallel because both have slope h/e . Hence, the correct option is (B).

Quick Tip to Solve: In a stopping-potential versus frequency graph, compare the coefficient h/e , not the metal-dependent threshold frequency.

30(ii). The value of Planck's constant for this metal is

[1 mark]

- (A) $\frac{e}{m}$
- (B) $\frac{1}{me}$
- (C) me
- (D) $\frac{m}{e}$

Correct Answer: (C) me

Solution:

Concept:

- The maximum photoelectron kinetic energy satisfies $eV_0 = h(\nu - \nu_0)$, where e is the magnitude of electron charge and ν_0 is threshold frequency.
- For a straight-line graph, slope is the coefficient of the horizontal-axis variable after the equation is written as $y = mx + b$.

Step 1: Identify the graph's slope Here the vertical quantity is V_0 , and the horizontal quantity is ν . Rearranging the photoelectric equation gives

$$V_0 = \frac{h}{e}\nu - \frac{h\nu_0}{e}.$$

Comparison with the straight-line equation shows that the given slope m equals h/e ; the threshold frequency affects the intercept only.

Step 2: Isolate Planck's constant Multiply the slope relation by elementary charge:

$$m = \frac{h}{e} \Rightarrow h = me.$$

The units confirm this result: the slope has units V s, so multiplying by charge gives C V s = J s. The ratios e/m , $1/(me)$, and m/e do not satisfy the slope equation.

Step 3: Conclusion Planck's constant is $h = me$. Hence, the correct option is (C).

Quick Tip to Solve: Read both graph axes before using its slope: a V_0 -versus- ν slope must be multiplied by e to obtain h .

30(iii). The intercepts on ν -axis and V_0 -axis of the graph are respectively:

[1 mark]

- (A) $\nu_0, \frac{h\nu_0}{e}$
- (B) $\nu_0, h\nu_0$
- (C) $\frac{h\nu_0}{e}, \nu_0$
- (D) $h\nu_0, \nu_0$

Correct Answer: (A) $\nu_0, \frac{h\nu_0}{e}$

Solution:

Concept:

- The stopping-potential line is $V_0 = (h/e)\nu - h\nu_0/e$, where ν_0 is the threshold frequency.
- An axis intercept is found by setting the other coordinate to zero. A signed intercept coordinate can be negative even though its distance from the origin is positive.

Step 1: Find the frequency-axis intercept Set $V_0 = 0$ in the line equation:

$$0 = \frac{h}{e}(\nu - \nu_0) \Rightarrow \nu = \nu_0.$$

The intercept on the frequency axis is therefore the positive threshold frequency, as shown by the point where the printed line meets that axis.

Step 2: Interpret the vertical-axis intercept Extrapolate to $\nu = 0$:

$$V_0 = -\frac{h\nu_0}{e}.$$

The dashed extension meets the vertical axis below the origin. Its signed coordinate is negative, while the intercept length is $h\nu_0/e$. The printed options give positive quantities, so option (A) represents the intended intercept magnitudes. Strictly, none gives the signed pair. Option (B) gives energy instead of voltage; (C) and (D) put quantities with incorrect dimensions on the axes.

Step 3: Conclusion The intercept magnitudes are ν_0 and $h\nu_0/e$. With the printed options interpreted as magnitudes, the correct option is (A). The signed vertical intercept is $-h\nu_0/e$.

Quick Tip to Solve: Set the other coordinate to zero for each intercept, and retain the minus sign when giving the vertical coordinate rather than its magnitude.

30(iii). When the wavelength of a photon is doubled, how many times its wave number and frequency become, respectively? [1 mark]

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

Correct Answer: (B) $\frac{1}{2}, \frac{1}{2}$

Solution:

Concept:

- Wave number is inversely proportional to wavelength: $\bar{\nu} = 1/\lambda$. The angular wave number $k = 2\pi/\lambda$ has the same inverse dependence.
- For a photon in vacuum, $c = \nu\lambda$, where c is the constant speed of light and ν is frequency.

Step 1: Find the change in wave number Let the original wavelength be λ , so the new wavelength is $\lambda' = 2\lambda$. Then

$$\frac{\bar{\nu}'}{\bar{\nu}} = \frac{1/(2\lambda)}{1/\lambda} = \frac{1}{2}.$$

Thus wave number is halved, whether it is defined using $1/\lambda$ or $2\pi/\lambda$.

Step 2: Find the change in frequency The speed of light remains the same, giving

$$\nu' = \frac{c}{2\lambda} = \frac{\nu}{2}.$$

Both quantities vary inversely with wavelength. Options (A) and (D) incorrectly double the wave number; option (C) incorrectly doubles the frequency. Neither quantity increases when the wavelength doubles.

Step 3: Conclusion The wave number and frequency each become $1/2$ of their initial values. Hence, the correct option is (B).

Quick Tip to Solve: A wavelength scale factor multiplies the denominators of both $1/\lambda$ and c/λ , so both requested ratios are its reciprocal.

30(iv). The momentum of a photon is $5.0 \times 10^{-29} \text{ kg m/s}$. Ignoring relativistic effects (if any), the wavelength of the photon is [1 mark]

- (A) $1.33 \mu\text{m}$
- (B) $3.3 \mu\text{m}$
- (C) $16.6 \mu\text{m}$
- (D) $13.3 \mu\text{m}$

Correct Answer: (D) $13.3 \mu\text{m}$

Solution:

Concept:

- The photon momentum-wavelength relation is $p = h/\lambda$, where $h = 6.63 \times 10^{-34} \text{ J s}$ is Planck's constant.
- Rearranging gives $\lambda = h/p$; one micrometre equals 10^{-6} m . A photon is not assigned a classical kinetic energy $p^2/(2m)$.

Step 1: Substitute the photon momentum Use the printed value $p = 5.0 \times 10^{-29} \text{ kg m s}^{-1}$:

$$\lambda = \frac{6.63 \times 10^{-34}}{5.0 \times 10^{-29}} \text{ m} = 1.326 \times 10^{-5} \text{ m}.$$

The exponent is $-34 - (-29) = -5$, and the quotient has units of length. The photon relation already applies directly, so the wording about relativistic effects requires no correction to this calculation.

Step 2: Convert to micrometres and compare Express the wavelength using the units in the options:

$$1.326 \times 10^{-5} \text{ m} = 13.26 \mu\text{m} \simeq 13.3 \mu\text{m}.$$

Option (A) is smaller by a factor of ten; (B) and (C) are inconsistent with the quotient h/p . The value matching the listed precision is $13.3 \mu\text{m}$.

Step 3: Conclusion The wavelength is approximately $13.3 \mu\text{m}$. Hence, the correct option is (D).

Quick Tip to Solve: Divide the powers of ten before converting metres to micrometres; here $10^{-5} \text{ m} = 10 \mu\text{m}$.

Section E (15 marks)

31(a). (i) A small conducting sphere A of radius r charged to a potential V , is enclosed by a spherical conducting shell B of radius R . If A and B are connected by a thin wire, calculate the final potential on sphere A and shell B.

(ii) Write two characteristics of equipotential surfaces. A uniform electric field of 50 N C^{-1} is set up in a region along $+x$ axis. If the potential at the origin $(0, 0)$ is 220 V , find the potential at a point $(4 \text{ m}, 3 \text{ m})$. [5 marks]

Solution:

Concept:

- For an isolated conducting sphere of radius a carrying charge Q , its potential relative to infinity is $V = Q/(4\pi\epsilon_0 a)$, where ϵ_0 is the permittivity of free space.
- Conductors joined by a wire have a common potential at electrostatic equilibrium. Charge is conserved in an isolated system, and excess charge resides on its outermost conducting surface

when the cavity contains no isolated charge.

- An equipotential surface has the same potential at every point. Potential difference obeys $\Delta V = - \int \vec{E} \cdot d\vec{l}$, so in a uniform field $\Delta V = -\vec{E} \cdot \Delta\vec{r}$.

Step 1: (i) Express the initial charge on sphere A The small sphere is first charged to potential V . Taking infinity as the zero of potential, its initial charge is obtained from the capacitance of a sphere:

$$C_A = 4\pi\epsilon_0 r, \quad Q = C_A V = 4\pi\epsilon_0 r V.$$

The enclosing shell is understood to be initially uncharged, as usual when no charge on the shell is specified. Enclosing A can induce charges on the shell, but it cannot change the total charge Q of the isolated sphere-shell system.

Step 2: (i) Redistribute charge after joining the conductors Connecting A and B allows charge to flow until their potentials become equal. The sphere, wire and shell then form a single conductor. In equilibrium, the electric field in the enclosed cavity is zero, since the cavity has no separate isolated charge. The net excess charge Q therefore resides on the outer surface of B, whose radius is R . The potential throughout the interior equals the shell's surface potential. Thus, using the unchanged total charge,

$$V_A^f = V_B^f = \frac{Q}{4\pi\epsilon_0 R} = \frac{4\pi\epsilon_0 r V}{4\pi\epsilon_0 R}.$$

The enlarged outer radius increases the capacitance of the connected system from $4\pi\epsilon_0 r$ to $4\pi\epsilon_0 R$. Consequently, the common potential is reduced by the factor r/R for a positive initial potential.

Step 3: (ii) State two characteristics of equipotential surfaces First, no work is done in moving a test charge along an equipotential surface: any two points on it have $\Delta V = 0$, and hence $W = q\Delta V = 0$. Second, the electric field is perpendicular to an equipotential surface wherever the field is nonzero. A tangential field component would do work along the surface and produce a potential difference, contradicting its constant potential.

Step 4: (ii) Use the displacement parallel to the electric field The field is $\vec{E} = 50\hat{i} \text{ N C}^{-1}$, while the displacement from the origin to P is $\Delta\vec{r} = (4\hat{i} + 3\hat{j}) \text{ m}$. The displacement in the y direction makes no contribution because it is perpendicular to the field. Therefore,

$$\begin{aligned} V_P - V_O &= -\vec{E} \cdot \Delta\vec{r} \\ &= -(50 \times 4 + 0 \times 3) \text{ V} \\ &= -200 \text{ V}, \\ V_P &= (220 - 200) \text{ V}. \end{aligned}$$

The negative potential change is consistent with potential decreasing along the direction of the electric field. Using the full distance $\sqrt{4^2 + 3^2} = 5 \text{ m}$ would be incorrect; only its component along $+x$ matters.

Step 5: Conclusion (i) The final potentials are $V_A^f = V_B^f = rV/R$. (ii) Motion along an equipotential surface requires no work, and the electric field is normal to the surface. The potential at $(4 \text{ m}, 3 \text{ m})$ is 20 V .

Quick Tip to Solve: For connected nested conductors, conserve total charge and use the outermost radius for the final potential. In a uniform field along x , calculate the potential change from $-E\Delta x$ alone.

31(b). (i) What is difference between an open surface and a closed surface? Draw elementary surface vector $d\vec{S}$ for a spherical surface S .

(ii) Define electric flux through a surface. Give the significance of a Gaussian surface. A charge outside a Gaussian surface does not contribute to total electric flux through the surface. Why?

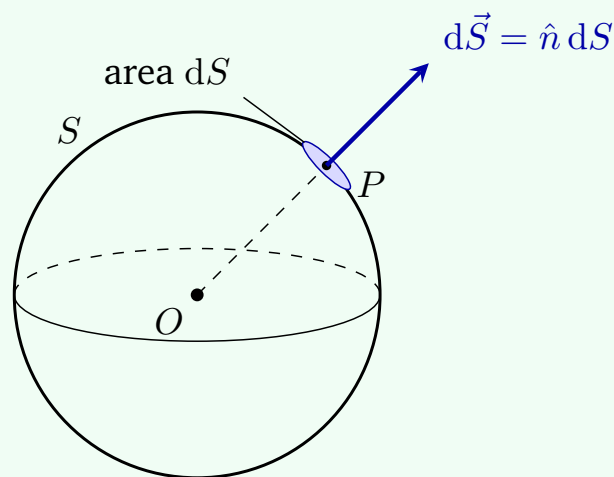
(iii) A small spherical shell S_1 has point charges $q_1 = -3\mu\text{C}$, $q_2 = -2\mu\text{C}$ and $q_3 = 9\mu\text{C}$ inside it. This shell is enclosed by another big spherical shell S_2 . A point charge Q is placed in between the two surfaces S_1 and S_2 . If the electric flux through the surface S_2 is four times the flux through surface S_1 , find charge Q . [5 marks]

Solution:

Concept:

- An elementary area vector is $d\vec{S} = \hat{n} dS$, where dS is the small area and $\hat{n}$ is its unit normal. For a closed surface, the normal is chosen outward.
- Electric flux through a surface is $\Phi_E = \int_S \vec{E} \cdot d\vec{S}$. It is the surface integral of the normal component of the electric field $\vec{E}$, and its SI unit is $\text{N m}^2 \text{C}^{-1}$.
- Gauss's law gives $\oint_S \vec{E} \cdot d\vec{S} = q_{\text{enc}}/\epsilon_0$, where q_{enc} is the algebraic charge enclosed by the closed surface and ϵ_0 is the permittivity of free space.

Step 1: (i) Distinguish the surfaces and draw the area vector An open surface has a boundary edge and does not completely enclose a volume, for example a plane circular disc or a hemispherical surface without its base. A closed surface has no boundary edge and completely encloses a volume, for example the entire surface of a sphere. At a small element of a spherical surface S , the normal lies along the radius through that element. Thus $d\vec{S}$ is perpendicular to the local tangent plane and points radially outward. The sketch shows the small area element and its outward normal at P .



outward normal is radial

Elementary outward surface vector on the spherical surface S

Step 2: (ii) Define flux and explain the Gaussian surface Electric flux measures the electric field passing normally through a surface. For a small element, $d\Phi_E = E dS \cos \theta$, where θ is the angle between $\vec{E}$ and $d\vec{S}$. Summing over the entire surface gives

$$\Phi_E = \int_S E \cos \theta dS.$$

A Gaussian surface is an imaginary closed surface chosen to apply Gauss's law. Its significance is that total outward flux depends only on the net enclosed charge. A suitable surface, chosen using the symmetry of a charge distribution, also simplifies the flux integral and enables calculation of the electric field. The surface need not be a physical shell or a conductor.

Step 3: (ii) Explain why an external charge gives zero net flux For the field of a charge outside a closed Gaussian surface, no source charge lies inside that surface. Gauss's law applied to that charge's field therefore gives zero net flux. In field-line language, every line that enters the surface also leaves it: the entering flux is negative and the leaving flux is positive, and their contributions cancel. The external charge can produce a nonzero field at individual points on the surface; it is only its total flux through the closed surface that vanishes.

Step 4: (iii) Relate the enclosed charges to the two fluxes The smaller surface encloses all three stated charges, whose algebraic sum is

$$q_{\text{in}} = q_1 + q_2 + q_3 = (-3 - 2 + 9) \mu\text{C} = 4 \mu\text{C}.$$

The charge Q lies outside S_1 , so it contributes zero net flux through S_1 , but lies inside S_2 , so it must be included for S_2 . Consequently,

$$\Phi_1 = \frac{4 \times 10^{-6} \text{ C}}{\epsilon_0}, \quad \Phi_2 = \frac{4 \times 10^{-6} \text{ C} + Q}{\epsilon_0}.$$

Substitute the condition $\Phi_2 = 4\Phi_1$, and cancel the common permittivity:

$$\begin{aligned} 4 \times 10^{-6} \text{ C} + Q &= 4(4 \times 10^{-6} \text{ C}), \\ Q &= (16 - 4) \times 10^{-6} \text{ C}. \end{aligned}$$

Step 5: Conclusion A closed surface encloses a volume and has an outward area normal; an open surface has an edge. Flux is the integral of $\vec{E} \cdot d\vec{S}$, and a Gaussian surface relates its net flux to enclosed charge only. The required charge between the two spherical surfaces is $Q = +12 \mu\text{C}$.

Quick Tip to Solve: Write the algebraic enclosed charge separately for each surface before using the flux ratio. Here $\Phi_2/\Phi_1 = 4$ makes the additional charge $Q = (4 - 1)(q_1 + q_2 + q_3)$.

32(a). (i) What is the source of force acting on a current-carrying conductor placed in a magnetic field? Obtain the expression for force acting between two long straight parallel conductors carrying steady currents and hence define 'ampere'.

(ii) A point charge q is moving with velocity $\vec{v}$ in a uniform magnetic field $\vec{B}$. Find the work done by the magnetic force on the charge.

(iii) Explain the necessary conditions in which the trajectory of a charged particle is helical in a uniform magnetic field. [5 marks]

Solution:

Concept:

- A moving charge experiences the magnetic Lorentz force $\vec{F} = q\vec{v} \times \vec{B}$. The magnetic forces on the drifting charge carriers give the force $\vec{F} = I\vec{\ell} \times \vec{B}$ on a straight conductor.
- A long straight wire carrying current I produces magnetic field $B = \mu_0 I / (2\pi d)$ at perpendicular

distance d in vacuum, where μ_0 is the permeability of free space.

- Magnetic force is perpendicular to velocity, so its power is zero. A nonzero velocity component perpendicular to a uniform field gives circular motion, while a parallel component remains constant.

Step 1: (i) Identify the microscopic source of the force Current consists of charge carriers drifting through the conductor. Each carrier experiences a magnetic force, and interaction with the material transfers this force to the conductor. To see the macroscopic result, let n be the carrier number density, A the cross-sectional area, q_c the signed carrier charge and $\vec{v}_d$ its drift velocity. A length ℓ contains $nA\ell$ carriers, so

$$\vec{F} = nA\ell q_c \vec{v}_d \times \vec{B} = I\vec{\ell} \times \vec{B}.$$

Here $\vec{\ell}$ points in the conventional-current direction. Thus the force originates from the magnetic force on moving charges, not from a magnetic force on stationary ions.

Step 2: (i) Derive the force between parallel conductors Consider two very long parallel wires in vacuum separated by d , carrying steady currents I_1 and I_2 . The field produced by the first wire at the second is

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

This field is perpendicular to the second wire. Therefore a length ℓ of that wire experiences

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

The first wire experiences an equal force in the opposite direction. Applying the right-hand rule to the field and then $I\vec{\ell} \times \vec{B}$ shows that currents in the same direction attract, whereas currents in opposite directions repel.

Step 3: (i) State the force-based definition of ampere For $I_1 = I_2 = 1$ A and $d = 1$ m, using $\mu_0 = 4\pi \times 10^{-7}$ N A⁻² gives

$$\frac{F}{\ell} = 2 \times 10^{-7} \text{ N m}^{-1}.$$

In the force-based definition requested here, one ampere is the constant current which, if maintained in each of two straight parallel conductors of infinite length and negligible circular cross-section placed one metre apart in vacuum, produces a force of 2×10^{-7} N per metre between them.

Step 4: (ii) Evaluate the work done by the magnetic force During a small time dt , the charge moves through $d\vec{r} = \vec{v} dt$. Hence

$$dW = \vec{F} \cdot d\vec{r} = q(\vec{v} \times \vec{B}) \cdot \vec{v} dt = 0, \quad W = \int dW = 0.$$

The magnetic force changes the direction of motion but cannot change the particle's speed or kinetic energy. This conclusion also includes motion along the field, when the force itself vanishes.

Step 5: (iii) Resolve the velocity to obtain a helix Let a particle of nonzero charge q and mass m enter a nonzero uniform magnetic field at angle θ to the field. For a helical trajectory it must have both $v_\perp = v \sin \theta \neq 0$ and $v_\parallel = v \cos \theta \neq 0$, with no other force disturbing the motion. Thus the velocity is neither parallel nor perpendicular to the field. The perpendicular component produces uniform circular motion, while the parallel component advances the particle uniformly along the field. In the nonrelativistic case,

$$r = \frac{mv_\perp}{|q|B}, \quad T = \frac{2\pi m}{|q|B}, \quad p = |v_\parallel|T.$$

Their superposition is a helix of radius r and pitch p , with its axis parallel to the magnetic field. If

$v_{\parallel} = 0$, the path is a circle; if $v_{\perp} = 0$, it is a straight line.

Step 6: Conclusion The conductor force comes from the Lorentz force on drifting carriers. Parallel currents exert $F/\ell = \mu_0 I_1 I_2 / (2\pi d)$, attracting for like directions and repelling for opposite directions; the force-based ampere corresponds to $2 \times 10^{-7} \text{ N m}^{-1}$ at one metre separation. Magnetic work is $W = 0$. A helix requires nonzero parallel and perpendicular velocity components in a uniform magnetic field.

Quick Tip to Solve: For parallel wires, find the field of one wire and apply $I\ell B$ to the other. For particle motion, separate the initial velocity into its parallel and perpendicular components before deciding the trajectory.

OR

32(b). (i) A current carrying loop can be considered as a magnetic dipole placed along its axis. Explain.

(ii) Obtain the relation for magnetic dipole moment $\vec{M}$ of current carrying coil. Give the direction of $\vec{M}$.

(iii) A current carrying coil is placed in an external uniform magnetic field. The coil is free to turn in the magnetic field. What is the net force acting on the coil? Obtain the orientation of the coil in stable equilibrium. Show that in this orientation the flux of the total field (field produced by the loop + external field) through the coil is maximum. [5 marks]

Solution:

Concept:

- A localized current loop has the distant magnetic field of a magnetic dipole. Its magnetic dipole moment is $\vec{M} = NIA\hat{n}$, where N is the number of turns, I the current, A the area of each turn and $\hat{n}$ its oriented unit normal.
- In a uniform external magnetic field, a closed current loop has zero net force but torque $\vec{\tau} = \vec{M} \times \vec{B}_{\text{ext}}$. Its orientational potential energy is $U = -\vec{M} \cdot \vec{B}_{\text{ext}}$.
- The external flux through one plane turn is $\Phi_{\text{ext}} = B_{\text{ext}} A \cos \theta$, where θ is the angle between its positive normal and the field. For a rigid coil carrying a fixed current, the self-flux stays unchanged as the coil turns.

Step 1: (i) Compare the loop field with a dipole field A current loop has magnetic field lines like those of a short bar magnet. Viewed from one face, an anticlockwise current makes that face act as a north pole; the opposite face acts as a south pole. Its magnetic axis is therefore the axis perpendicular to the loop's plane. This correspondence can also be checked quantitatively. For a circular loop of radius R , the field at axial distance x from its centre is

$$B_{\text{axis}} = \frac{\mu_0 I R^2}{2(R^2 + x^2)^{3/2}}.$$

Far from the loop, where $x \gg R$, and with $A = \pi R^2$,

$$B_{\text{axis}} \simeq \frac{\mu_0 I R^2}{2x^3} = \frac{\mu_0}{4\pi} \frac{2IA}{x^3}.$$

This equals the axial dipole field $\mu_0(2M)/(4\pi x^3)$ for $M = IA$. Thus a small loop behaves as a magnetic dipole directed along its axis; the point-dipole approximation applies at distances large

compared with the loop size.

Step 2: (ii) Derive the magnetic moment from the torque Consider a rectangular loop of sides a and b , with area $A = ab$. Let its normal make angle θ with a uniform external field, and choose the two sides of length b perpendicular to that field. Each of these sides experiences force IbB_{ext} ; the forces are opposite and their perpendicular separation is $a \sin \theta$. They form a couple with torque

$$\tau = (IbB_{\text{ext}})(a \sin \theta) = IAB_{\text{ext}} \sin \theta.$$

Comparing with the dipole relation $\tau = MB_{\text{ext}} \sin \theta$ gives $M = IA$. The torques of N identical turns add, giving

$$\vec{M} = NIA\hat{n}, \quad [M] = \text{A m}^2.$$

The direction follows the right-hand grip rule: curl the fingers along the conventional current; the extended thumb points along $\vec{M}$, normal to the coil's plane and toward its north face.

Step 3: (iii) Find the net force and equilibrium orientations A small current element has force $d\vec{F} = I d\vec{\ell} \times \vec{B}_{\text{ext}}$. Because the external field is uniform, the net force on a closed turn is

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

This is true for the complete coil as well. There can still be a torque, since the opposing forces act at different points. Using $\tau = MB_{\text{ext}} \sin \theta$, zero torque is obtained for $\theta = 0$ or $\theta = \pi$. To distinguish stability, use

$$U(\theta) = -MB_{\text{ext}} \cos \theta, \quad \frac{d^2U}{d\theta^2} = MB_{\text{ext}} \cos \theta.$$

At $\theta = 0$, the energy has a minimum and a small rotation produces a restoring torque. Thus stable equilibrium has $\vec{M}$ parallel to $\vec{B}_{\text{ext}}$, so the plane of the coil is perpendicular to the external field. At $\theta = \pi$, the energy is a maximum, giving unstable equilibrium.

Step 4: (iii) Maximize the flux of the total field Choose the coil's positive area normal along $\vec{M}$. For a fixed current and a rigid coil, the field produced by the coil rotates with it, so its self-flux Φ_{self} through a turn is independent of its orientation in space. Fluxes from the self-field and the external field add:

$$\Phi_{\text{total}}(\theta) = \Phi_{\text{self}} + B_{\text{ext}}A \cos \theta.$$

Since $\cos \theta \leq 1$, the maximum occurs at $\theta = 0$:

$$\Phi_{\text{total,max}} = \Phi_{\text{self}} + B_{\text{ext}}A.$$

Equivalently, for an N -turn coil of self-inductance L , the total flux linkage is $LI + NB_{\text{ext}}A \cos \theta$, also maximal at $\theta = 0$. Hence the stable orientation found from the torque and energy is precisely the orientation of maximum total flux.

Step 5: Conclusion A current loop behaves as an axial magnetic dipole with $\vec{M} = NIA\hat{n}$, directed by the right-hand grip rule. Its net force in a uniform field is zero. Stable equilibrium requires $\vec{M} \parallel \vec{B}_{\text{ext}}$, or the coil plane perpendicular to the field; then the total flux is maximum, $\Phi_{\text{self}} + B_{\text{ext}}A$ per turn.

Quick Tip to Solve: Measure θ from the coil's normal, not its plane. At stable equilibrium the torque is zero, the energy $-MB \cos \theta$ is minimum, and the external flux $BA \cos \theta$ is maximum.

33(a). (i) A thin pencil of length $f/4$ is placed coinciding with the principal axis of a mirror of focal length f . The image of the pencil is real and enlarged, just touches the pencil. Calculate the magnification produced by the mirror.

(ii) A ray of light is incident on a refracting face AB of a prism ABC at an angle of 45° . The ray emerges from face AC and the angle of deviation is 15° . The angle of prism is 30° . Show that the emergent ray is normal to the face AC from which it emerges out. Find the refraction index of the material of the prism.

[5 marks]

Solution:

Concept:

- A concave mirror forms an enlarged real image when the object lies between its focus and centre of curvature. With $f > 0$ denoting the magnitude of its focal length, the centre of curvature is at a distance $2f$ from the pole.
- For a real object and real image in front of the concave mirror, their positive distances U and V obey $1/f = 1/U + 1/V$. For a pencil along the axis, find the images of both ends and compare the image length with the object length.
- For a prism, $\delta = i + e - A$ and $r_1 + r_2 = A$, where i, e are the external angles, r_1, r_2 are the internal refraction angles, A is the prism angle and δ is the deviation. All ray angles are measured from the normal to the relevant face.
- Snell's law at the first face for incidence from air gives the refractive index $\mu = \sin i / \sin r_1$.

Step 1: (i) Locate the touching end of the pencil The mirror must be concave, since a convex mirror cannot form a real enlarged image of a real object. The image just touches the axial pencil, so the touching point is an endpoint that coincides with its own image. A point and its real image coincide at the centre of curvature:

$$\frac{1}{f} = \frac{1}{U} + \frac{1}{U} \Rightarrow U = 2f.$$

For enlargement, the pencil extends from this point towards the focus; if it extended away from the mirror beyond $2f$, its image would be diminished. Therefore its farther end is at $U_2 = 2f$, while its nearer end is at

$$U_1 = 2f - \frac{f}{4} = \frac{7f}{4}.$$

Step 2: (i) Calculate the images of the two ends The farther end at the centre of curvature has its image at $V_2 = 2f$. Apply the mirror relation to the nearer end:

$$\frac{1}{V_1} = \frac{1}{f} - \frac{1}{7f/4} = \frac{1}{f} - \frac{4}{7f} = \frac{3}{7f},$$

$$V_1 = \frac{7f}{3}.$$

Thus the pencil occupies distances from $7f/4$ to $2f$, while its image occupies distances from $2f$ to $7f/3$. They have exactly one common endpoint, as required by the question.

Step 3: (i) Compare the image and pencil lengths Subtract the image-end distances, because the pencil lies along the principal axis:

$$L_{\text{image}} = V_1 - V_2 = \frac{7f}{3} - 2f = \frac{f}{3}.$$

Relative to the original length $L = f/4$, the length magnification is

$$M = \frac{L_{\text{image}}}{L} = \frac{f/3}{f/4} = \frac{4}{3}.$$

The nearer object end becomes the farther image end: the endpoint order is reversed. If oriented axial segments are used, the signed ratio is $(V_2 - V_1)/(U_2 - U_1) = -4/3$; the enlargement factor is its magnitude $4/3$.

Step 4: (ii) Determine the angle of emergence Substitute the printed values $i = 45^\circ$, $\delta = 15^\circ$ and $A = 30^\circ$ in the prism deviation relation:

$$e = \delta + A - i = 15^\circ + 30^\circ - 45^\circ = 0^\circ.$$

Since e is measured from the normal to AC, zero emergence angle means that the emergent ray is normal to face AC. Snell's law there gives $\mu \sin r_2 = \sin e = 0$, so $r_2 = 0^\circ$ as well: the internal ray also reaches AC normally.

Step 5: (ii) Apply Snell's law at the first face The two internal angles add to the prism angle, giving

$$r_1 = A - r_2 = 30^\circ - 0^\circ = 30^\circ.$$

At AB, use incidence from air into the prism:

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

No minimum-deviation assumption is needed: the two external angles are unequal, and the second face produces no bending because incidence there is normal.

Step 6: Conclusion (i) The pencil's image is $\boxed{4/3}$ times its length, with the end order reversed (signed axial ratio $-4/3$). (ii) $\boxed{e = 0^\circ}$, so emergence is normal to AC, and the prism has refractive index $\boxed{\mu = \sqrt{2} \simeq 1.414}$.

Quick Tip to Solve: For an axial pencil, image both ends before taking a length ratio; here the touching end is at $2f$. For the prism, find e from $\delta = i + e - A$ before applying Snell's law.

33(b). (i) Light consisting of two wavelengths 600 nm and 480 nm is used to obtain interference fringes in a double slit experiment. The screen is placed 1.0 m away from slits which are 1.0 nm apart.

(1) Calculate the distance of the third bright fringe on the screen from the central maximum for wavelength 600 nm.

(2) Find the least distance from the central maximum where the bright fringes due to both the wavelengths coincide.

(ii) (1) Draw the variation of intensity with angle of diffraction in single slit diffraction pattern. Write the expression for value of angle corresponding to zero intensity locations.

(2) In what way diffraction of light waves differs from diffraction of sound waves?

[5 marks]

Solution:

Concept:

- For two coherent slits separated by d , a bright fringe requires path difference $\Delta = m\lambda$. In the far field, $\Delta = d \sin \theta$; only for small angles does the screen position become $y_m \simeq m\lambda D/d$, where D is the screen distance.
- Bright fringes of two wavelengths coincide when $m\lambda_1 = n\lambda_2$, for integer orders m, n . The path difference between waves from the two slits can never exceed their separation: $|\Delta| \leq d$.
- For a single slit of width a , $I(\theta) = I_0(\sin \alpha/\alpha)^2$, where $\alpha = \pi a \sin \theta/\lambda$. Diffraction is appreciable when the opening or obstacle size is comparable with the wavelength.

Step 1: (i)(1) Check the printed slit separation and third order The official question prints $d = 1.0 \text{ nm} = 10^{-9} \text{ m}$, with $D = 1.0 \text{ m}$ and $\lambda_1 = 600 \text{ nm}$. Keep that printed unit. A third bright fringe would require

$$\Delta = 3\lambda_1 = 1800 \text{ nm}, \quad \sin \theta = \frac{3\lambda_1}{d} = 1800.$$

Since $|\sin \theta| \leq 1$, this fringe cannot exist for the printed separation. Merely inserting the data into the small-angle formula gives

$$y_3^{\text{formal}} = \frac{3(600 \times 10^{-9})(1.0)}{1.0 \times 10^{-9}} = 1.8 \times 10^3 \text{ m}.$$

This is the formal arithmetic result, but it is not a physical fringe position: $y/D = 1800$ violates the small-angle approximation, and the required path difference already exceeds d .

Step 2: (i)(2) Find the first positive common order Excluding the central maximum, let the bright orders be positive integers m for 600 nm and n for 480 nm. Coincidence requires

$$600m = 480n \quad \Rightarrow \quad 5m = 4n.$$

The smallest pair is $m = 4$, $n = 5$, corresponding to $\Delta = 2400 \text{ nm}$. The usual small-angle substitution would yield

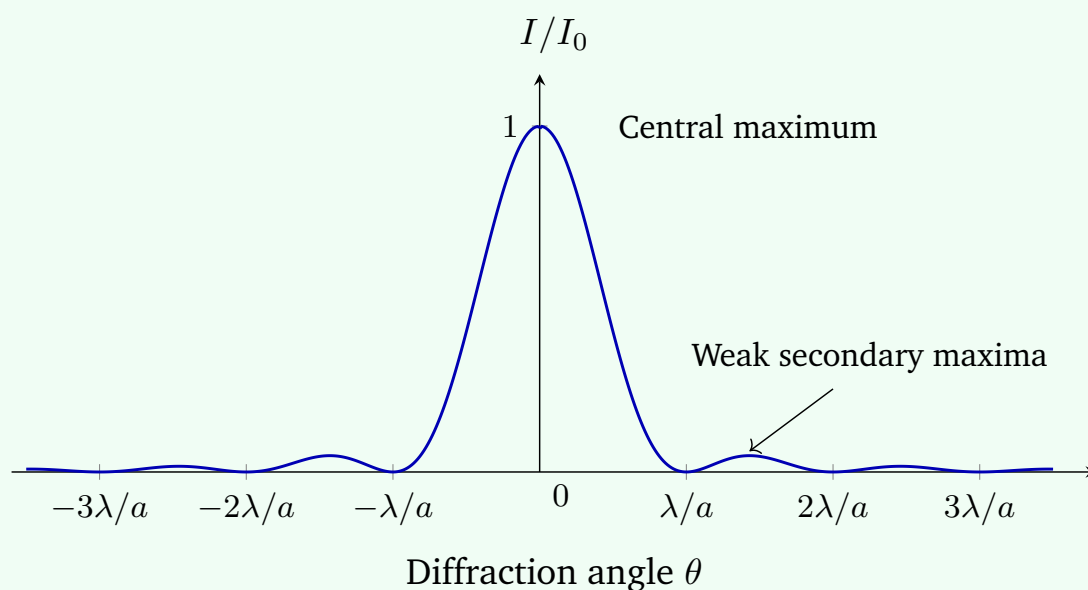
$$y_{\text{coinc}}^{\text{formal}} = \frac{4(600 \times 10^{-9})(1.0)}{1.0 \times 10^{-9}} = 2.4 \times 10^3 \text{ m}.$$

Again, $2400 \text{ nm} > d$, so this positive-order coincidence is impossible with the printed data. The central maximum, at $y = 0$, is the only common bright order; there is no least positive coincidence distance. These inconsistencies arise in the printed numerical setup, not from changing the order condition.

Step 3: (ii)(1) Locate the single-slit minima and sketch intensity Across the slit, waves interfere destructively when its edge-to-edge path difference is a nonzero integer multiple of the wavelength. Therefore the zero-intensity directions satisfy

$$a \sin \theta_m = m\lambda, \quad m = \pm 1, \pm 2, \pm 3, \dots,$$

or $\theta_m = \sin^{-1}(m\lambda/a)$, for allowed orders with $|m\lambda/a| \leq 1$. For small angles, $\theta_m \simeq m\lambda/a$ in radians. The value $m = 0$ is excluded: the limit $\sin \alpha/\alpha \rightarrow 1$ gives the central maximum I_0 , not a minimum. The central maximum lies between the first minima on either side, so its angular width is approximately $2\lambda/a$. The secondary maxima have smaller, decreasing intensities; each secondary lobe lies between successive minima and is approximately half as wide as the central lobe. The graph uses the small-angle scale for its horizontal labels.



Single-slit intensity versus diffraction angle; horizontal labels use the small-angle approximation.

Step 4: (ii)(2) Compare diffraction of light and sound Both light and sound spread into the geometrical shadow region by diffraction, according to the same wave principle. Their everyday behaviour differs because their wavelengths differ greatly. Visible light has a wavelength of order 10^{-7} m, so pronounced diffraction requires very narrow slits or comparably small obstacles. Audible sound has much larger wavelengths, often comparable to doors and ordinary obstacles, so it bends appreciably around them and is readily heard beyond an obstruction. Thus the difference is the observable amount of spreading for ordinary openings, rather than the presence or absence of diffraction.

Step 5: Conclusion With the printed $d = 1.0$ nm, the third bright fringe and any nonzero common bright order do not exist. The formal small-angle values are 1800 m and 2400 m, respectively, but are physically invalid here. Single-slit minima satisfy $a \sin \theta_m = m\lambda$, $m \neq 0$; sound diffracts noticeably through everyday openings because its wavelength is much larger than that of visible light.

Quick Tip to Solve: Before using $y_m = m\lambda D/d$, check $m\lambda/d \ll 1$. For two colours, reduce their wavelength ratio to find the first common orders, then check that the required path difference is possible.