

CBSE Class 12 Physics Question Paper 2026 with Solution PDF-Set 55/5/3



Question Paper with Solutions

Conducted by the Central Board of Secondary Education (CBSE)

Time Allowed: 3 hours

Maximum Marks: 70

General Instructions

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

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

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

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

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

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

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

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

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

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

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

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

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

Section A (16 marks)

1. A 500 nm photon is incident normally on a perfectly reflecting surface and is reflected. The value of momentum transferred to the surface is: [1 mark]

(A) $3.87 \times 10^{-43} \text{ kg ms}^{-1}$

(B) $2.5 \times 10^{-30} \text{ kg ms}^{-1}$

(C) $2.65 \times 10^{-27} \text{ kg ms}^{-1}$

(D) $1.33 \times 10^{-27} \text{ kg ms}^{-1}$

Correct Answer: (C) $2.65 \times 10^{-27} \text{ kg ms}^{-1}$

Solution:

Concept:

- A photon of wavelength λ has momentum magnitude $p = h/\lambda$, where h is Planck's constant.
- At normal reflection, the photon reverses direction. Conservation of momentum therefore gives the surface a momentum $2p$ along the incident beam.

Step 1: Calculate the incident photon momentum Convert the wavelength before substitution:
 $500 \text{ nm} = 5.00 \times 10^{-7} \text{ m}$.

$$p = \frac{6.63 \times 10^{-34}}{5.00 \times 10^{-7}} = 1.326 \times 10^{-27} \text{ kg m s}^{-1}.$$

Step 2: Account for the reversal on reflection Taking the incident direction as positive, the photon momentum changes from $+p$ to $-p$. The surface receives the opposite change:

$$\Delta p_{\text{surface}} = 2p = 2.652 \times 10^{-27} \text{ kg m s}^{-1}.$$

Option (D) is approximately the incident momentum alone, appropriate to absorption rather than perfect reflection. Options (A) and (B) have magnitudes inconsistent with $2h/\lambda$.

Step 3: Conclusion The momentum transferred is $2.65 \times 10^{-27} \text{ kg m s}^{-1}$, in the incident direction. Hence, the correct option is (C).

Quick Tip to Solve: For normal incidence, use h/λ for absorption and $2h/\lambda$ for perfect reflection.

2. A good diode checked by a multimeter should indicate: [1 mark]

(A) high resistance in reverse bias and a low resistance in forward bias

(B) high resistance in both forward bias and reverse bias

(C) low resistance in both reverse bias and forward bias

(D) high resistance in forward bias and low resistance in reverse bias

Correct Answer: (A) high resistance in reverse bias and a low resistance in forward bias

Solution:

Concept:

- A p - n junction diode conducts readily in forward bias but carries only a small leakage current in reverse bias, below breakdown.

- For a multimeter resistance check, greater current for the applied test voltage corresponds to lower indicated resistance.

Step 1: Check the forward direction Forward bias lowers the junction potential barrier and narrows the depletion layer. Majority carriers can cross the junction readily, so a good diode indicates a low forward resistance.

Step 2: Reverse the test polarity Reverse bias raises the potential barrier and widens the depletion layer. The current is very small, so the indicated reverse resistance is high. High readings in both directions, as in (B), suggest an open diode; low readings in both, as in (C), suggest a shorted diode. Option (D) interchanges the normal forward and reverse behaviour.

Step 3: Conclusion A good diode indicates high resistance in reverse bias and low resistance in forward bias. Hence, the correct option is (A).

Quick Tip to Solve: Reverse the multimeter leads: a healthy diode changes from a low forward reading to a high reverse reading.

3. A square loop of side 0.50 m is placed in a uniform magnetic field of 0.4 T perpendicular to the plane of the loop. The loop is rotated through an angle of 60° in 0.2 s. The value of emf induced in the loop will be: [1 mark]

- (A) 5 V
- (B) 3.5 V
- (C) 2.5 V
- (D) Zero V

Correct Answer: For the usual flux-changing rotation, the average emf is 0.25 V; this value is absent from the printed options.

Solution:

Concept:

- Magnetic flux through one loop is $\Phi = BA \cos \theta$, where θ is the angle between the magnetic field and the normal to the loop.
- Faraday's law gives the magnitude of average induced emf as $|\varepsilon_{av}| = |\Phi_f - \Phi_i| / \Delta t$.

Step 1: Calculate the change in magnetic flux The area is $A = (0.50)^2 = 0.25 \text{ m}^2$. Initially the field is normal to the loop, so $\theta_i = 0^\circ$. For the usual intended rotation that tilts its normal through 60° ,

$$\begin{aligned}\Phi_i &= (0.4)(0.25) = 0.100 \text{ Wb}, \\ \Phi_f &= (0.4)(0.25) \cos 60^\circ = 0.050 \text{ Wb}.\end{aligned}$$

Step 2: Evaluate the average emf and compare the options The stated time permits calculation of the average emf:

$$|\varepsilon_{av}| = \frac{0.100 - 0.050}{0.2} = 0.25 \text{ V}.$$

Options (A), (B) and (C) are 5, 3.5 and 2.5 V, respectively; none equals 0.25 V. Option (D) does not follow for this flux-changing rotation. Rotation about the loop's normal would instead leave the flux unchanged, but the printed question does not specify that axis. The options therefore do not supply a unique justified answer to the intended calculation.

Step 3: Conclusion With the standard interpretation, the average emf is 0.25 V. No printed option matches this result; the question as printed has inconsistent options and does not specify the rotation axis.

Quick Tip to Solve: Square the side first, use the angle to the loop's normal, and compare the calculated value with the printed options without changing a decimal.

4. The magnetic field in a plane electromagnetic wave travelling in glass ($n = 1.5$) is given by

$$B_y = (2 \times 10^{-7} \text{ T}) \sin(\alpha x + 1.5 \times 10^{11} t)$$

where x is in metres and t is in seconds. The value of α is:

[1 mark]

(A) $0.5 \times 10^3 \text{ m}^{-1}$

(B) $6.0 \times 10^2 \text{ m}^{-1}$

(C) $7.5 \times 10^2 \text{ m}^{-1}$

(D) $1.5 \times 10^3 \text{ m}^{-1}$

Correct Answer: (C) $7.5 \times 10^2 \text{ m}^{-1}$

Solution:

Concept:

- The wave speed in a medium of refractive index n is $v = c/n$, where c is the speed of light in vacuum.
- In the phase $kx + \omega t$, k is the wave number and ω is angular frequency; their magnitudes satisfy $v = \omega/k$.

Step 1: Identify the speed and angular frequency Comparing the printed phase with $kx + \omega t$ gives $k = \alpha$ and $\omega = 1.5 \times 10^{11} \text{ s}^{-1}$. In glass,

$$v = \frac{3.0 \times 10^8}{1.5} = 2.0 \times 10^8 \text{ m s}^{-1}.$$

Step 2: Determine the wave number

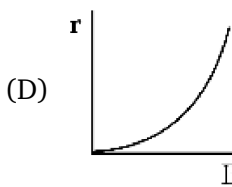
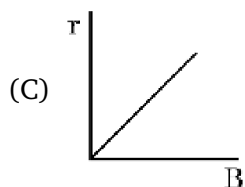
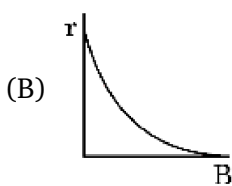
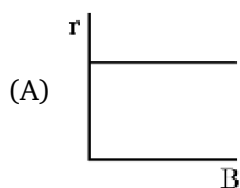
$$\alpha = \frac{\omega}{v} = \frac{1.5 \times 10^{11}}{2.0 \times 10^8} = 7.5 \times 10^2 \text{ m}^{-1}.$$

The plus sign in the phase indicates propagation toward decreasing x ; it does not change the positive wave-number magnitude. Option (A) uses the vacuum speed, ignoring glass. Options (B) and (D) do not satisfy $\omega/\alpha = c/n$. The magnetic-field amplitude is not needed to find α .

Step 3: Conclusion The value is $\alpha = 7.5 \times 10^2 \text{ m}^{-1}$. Hence, the correct option is (C).

Quick Tip to Solve: Read ω directly from the coefficient of t , then use $k = n\omega/c$ for the medium.

5. A charged particle is moving in a uniform magnetic field $\vec{B}$ with a constant speed v in a circular path of radius r . Which of the following graphs represents the variation of radius of the circle, with the magnitude of magnetic field $\vec{B}$? [1 mark]



Correct Answer: (B)



Solution:

Concept:

- For circular motion perpendicular to a uniform magnetic field, the magnetic force $|q|vB$ supplies the centripetal force mv^2/r .
- At fixed mass m , charge magnitude $|q|$ and speed v , the orbit radius satisfies $r = mv/(|q|B)$.

Step 1: Relate the radius to the magnetic field The magnetic force acts perpendicular to the velocity, changing its direction while keeping the speed constant. Equating the two force expressions gives

$$|q|vB = \frac{mv^2}{r} \Rightarrow r = \frac{mv}{|q|B}.$$

Step 2: Match the inverse dependence to the graph The product $rB = mv/|q|$ is constant, so increasing B decreases r . The graph is a decreasing rectangular hyperbola, approaching the axes asymptotically. Graph (A) incorrectly keeps r constant, while graphs (C) and (D) incorrectly make it increase with B . Only graph (B) shows the required inverse variation.

Step 3: Conclusion Since $r \propto 1/B$, the decreasing hyperbola represents the motion. Hence, the correct option is (B).

Quick Tip to Solve: If the magnetic field doubles at unchanged speed, the radius halves; use this check to identify the inverse graph.

6. Which of the following statements is *not* true for electric energy in ac form compared to that in dc form? [1 mark]

- (A) Production of ac is economical.
- (B) ac can be easily and efficiently converted from one voltage to the other.
- (C) ac can be transmitted economically over long distances.
- (D) ac is less dangerous.

Correct Answer: (D) ac is less dangerous.

Solution:

Concept:

- Alternating voltage can be stepped up or down efficiently using a transformer, which operates through changing magnetic flux.
- For a given transmitted power, a higher voltage permits a lower current and reduces the resistive loss $P_{\text{loss}} = I^2 R$ in the lines.

Step 1: Identify the accepted advantages of ac In the standard comparison, ac generation is economical, so (A) is true. Transformers provide efficient voltage conversion, making (B) true. Stepping up the transmission voltage reduces current and line losses for the same power; this is the basis of the economical long-distance transmission stated in (C).

Step 2: Examine the statement about danger The economic and voltage-conversion advantages do not imply that ac is less dangerous. Both ac and dc can cause serious electric shock; the effect depends on the current through the body, its path and duration. Power-frequency ac is not generally safer than dc under comparable conditions, so the unconditional claim in (D) is not true.

Step 3: Conclusion The statement “ac is less dangerous” is not a valid advantage of ac over dc. Hence, the correct option is (D).

Quick Tip to Solve: In an ac-versus-dc comparison, separate transformer and transmission advantages from claims about electric-shock safety.

7. The energy of an electron in an orbit in hydrogen atom is -3.4 eV . Its angular momentum in the orbit will be: [1 mark]

- (A) $\frac{3h}{2\pi}$
- (B) $\frac{2h}{\pi}$
- (C) $\frac{h}{\pi}$
- (D) $\frac{h}{2\pi}$

Correct Answer: (C) $\frac{h}{\pi}$

Solution:

Concept:

- In the Bohr model, the energy of the hydrogen electron in orbit n is $E_n = -13.6/n^2 \text{ eV}$, where n is a positive integer.
- The allowed orbital angular momentum is $L_n = nh/(2\pi)$, where h is Planck's constant.

Step 1: Determine the principal quantum number Substitute the given negative energy into the hydrogen energy formula:

$$-3.4 = -\frac{13.6}{n^2} \Rightarrow n^2 = 4 \Rightarrow n = 2.$$

Thus the electron is in the second Bohr orbit, not the ground-state orbit.

Step 2: Apply angular-momentum quantisation

$$L_2 = \frac{2h}{2\pi} = \frac{h}{\pi}.$$

Option (A) corresponds to $n = 3$, option (B) to $n = 4$, and option (D) to $n = 1$; these orbits have energies different from -3.4 eV. Only option (C) matches $n = 2$.

Step 3: Conclusion The angular momentum is h/π , equal to $2\hbar$. Hence, the correct option is (C).

Quick Tip to Solve: First obtain n from the ratio $13.6/|E|$; then multiply $h/(2\pi)$ by that n .

8. The rms and the average value of an ac voltage $V = V_0 \sin \omega t$ volt over a cycle respectively will be: [1 mark]

- (A) $\frac{V_0}{2}, \frac{V_0}{\sqrt{2}}$
 (B) $\frac{V_0}{\pi}, \frac{V_0}{2}$
 (C) $\frac{V_0}{\sqrt{2}}, 0$
 (D) $V_0, \frac{V_0}{\sqrt{2}}$

Correct Answer: (C) $\frac{V_0}{\sqrt{2}}, 0$

Solution:

Concept:

- The root mean square voltage is $V_{\text{rms}} = \sqrt{\langle V^2 \rangle}$, where the average is taken over one complete cycle.
- The mean voltage is the signed average $V_{\text{av}} = \langle V \rangle$; equal positive and negative half-cycles cancel.

Step 1: Calculate the rms voltage Squaring $V = V_0 \sin \omega t$ removes the sign of the voltage. Since the average of $\sin^2 \omega t$ over a full cycle is $1/2$,

$$V_{\text{rms}} = \sqrt{V_0^2 \langle \sin^2 \omega t \rangle} = \frac{V_0}{\sqrt{2}}.$$

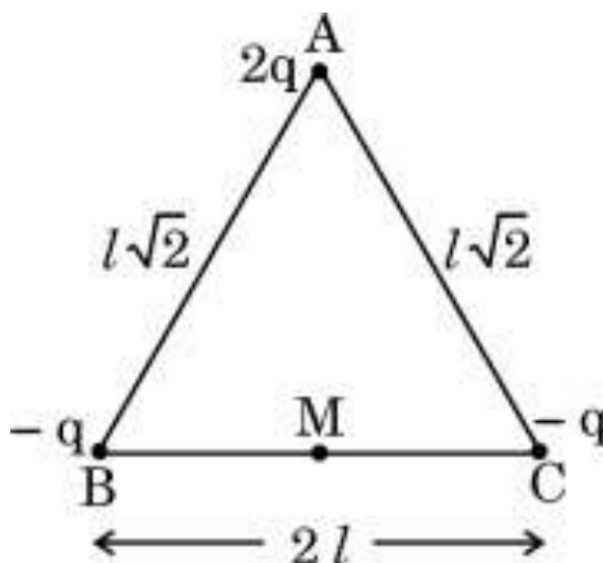
Step 2: Average the voltage over a complete cycle The areas above and below the time axis have equal magnitudes and opposite signs, so $V_{\text{av}} = 0$. Options (A), (B) and (D) all give nonzero averages

and therefore fail. Also, their first entries do not equal the rms value of a sine wave. A half-cycle average must not be used when the question specifies a complete cycle.

Step 3: Conclusion The rms and average voltages are respectively $V_0/\sqrt{2}$ and 0. Hence, the correct option is (C).

Quick Tip to Solve: For a full sine-wave cycle, average the signed voltage to get zero; square first when calculating the nonzero rms value.

9. The figure shows three point charges kept at the vertices of triangle ABC. The net electric field, due to this system of charges, at the midpoint M of base BC will be: [1 mark]



- (A) $\frac{q}{4\pi\epsilon_0 l^2}$ pointing along MA
 (B) $\frac{q}{\pi\epsilon_0 l^2}$ pointing along AM
 (C) $\frac{q}{2\pi\epsilon_0 l^2}$ pointing along AM
 (D) Zero

Correct Answer: (C) $\frac{q}{2\pi\epsilon_0 l^2}$ pointing along AM

Solution:

Concept:

- A charge Q produces field $E = |Q|/(4\pi\epsilon_0 r^2)$ at distance r .
- Fields add vectorially; they point away from positive charges and towards negative charges.

Step 1: Cancel the base-charge fields Since $BM = CM = l$, the two charges $-q$ produce equal, opposite fields at M, directed towards B and C. They cancel, leaving only the field of $2q$ at A.

Step 2: Find the apex contribution The isosceles triangle has $AM \perp BC$. Hence,

$$AM = \sqrt{AB^2 - BM^2} = \sqrt{2l^2 - l^2} = l.$$

The field at M due to the positive apex charge is

$$E_A = \frac{2q}{4\pi\epsilon_0 l^2} = \frac{q}{2\pi\epsilon_0 l^2},$$

directed along AM. Option (A) reverses the direction and halves the magnitude; (B) doubles the magnitude; (D) ignores the apex field.

Step 3: Conclusion The net field is $q/(2\pi\epsilon_0 l^2)$, pointing along AM. Hence, the correct option is (C).

Quick Tip to Solve: Cancel the base-charge fields first, then use the perpendicular height as the distance from A.

10. Consider the nuclear reaction $X \rightarrow Y + Z$. Let M_x , M_y and M_z be the masses of the three nuclei X, Y and Z respectively. Then which of the following relations hold true? [1 mark]

- (A) $(M_x - M_z) < M_y$
- (B) $(M_x - M_y) < M_z$
- (C) $M_x > (M_y + M_z)$
- (D) $M_x < (M_y + M_z)$

Correct Answer: (C) $M_x > (M_y + M_z)$

Solution:

Concept:

- Mass and energy are equivalent: a decrease ΔM in total rest mass releases energy $Q = \Delta M c^2$, where c is the speed of light.
- In a spontaneous nuclear breakup $X \rightarrow Y + Z$, the parent rest energy supplies the products' rest energies and their kinetic energies.

Step 1: Apply energy conservation to the breakup In the rest frame of X, with no external energy supplied, conservation of energy gives

$$M_x c^2 = M_y c^2 + M_z c^2 + K_y + K_z,$$

where K_y and K_z are the kinetic energies of the daughter nuclei. An energetically allowed decay has positive released energy.

Step 2: Compare the total rest masses The energy release is

$$Q = (M_x - M_y - M_z)c^2 > 0.$$

Thus the parent has more rest mass than the two daughters together. Options (A), (B) and (D) all

rearrange to $M_x < M_y + M_z$; that relation would require an external energy input and cannot describe the spontaneous breakup written here.

Step 3: Conclusion $M_x > (M_y + M_z)$. The lost rest mass supplies the energy released in the decay. Hence, the correct option is (C).

Quick Tip to Solve: For a one-parent spontaneous decay, subtract the sum of product rest masses from the parent mass; the difference must be positive.

11. Two points R and S are equidistant from two charges $+Q$ and $-2Q$. The work done in moving a charge $-Q$ from R to S is: [1 mark]

- (A) Zero
(B) $-\frac{Q}{4\pi\epsilon_0 d}$
(C) $\frac{Q}{4\pi\epsilon_0 d}$
(D) $\frac{3Q}{4\pi\epsilon_0 d}$

Correct Answer: (A) Zero

Solution:

Concept:

- Electric potential is a scalar sum: $V = \sum_i Q_i / (4\pi\epsilon_0 r_i)$, where r_i is the distance to source charge Q_i .
- Moving a charge q_0 between two points changes its potential energy by $\Delta U = q_0(V_S - V_R)$. The electrostatic work is $-\Delta U$.

Step 1: Compare the potentials at R and S The stated equal distances of R and S from the source charges make their potentials identical. Writing the common distance as d , each point has potential

$$V_R = V_S = \frac{1}{4\pi\epsilon_0} \left(\frac{Q}{d} - \frac{2Q}{d} \right) = -\frac{Q}{4\pi\epsilon_0 d}.$$

The potential itself is nonzero, but its difference between R and S is zero.

Step 2: Calculate the work for the moving charge For the charge $q_0 = -Q$, the work done by an external agent in moving it slowly is

$$W_{\text{ext}} = q_0(V_S - V_R) = (-Q)(0) = 0.$$

The electric field also does zero net work between these equal-potential points. Option (B) is the common potential, not the work; the nonzero quantities in (C) and (D) likewise cannot represent work for zero potential difference.

Step 3: Conclusion The work done in moving the charge from R to S is 0 J. Hence, the correct option is (A).

Quick Tip to Solve: Compare the endpoint potentials before multiplying by the moving charge; a nonzero common potential still gives zero work.

12. The radius of a nucleus of mass number 125 is:

[1 mark]

- (A) 6.0 fm
- (B) 30 fm
- (C) 72 fm
- (D) 150 fm

Correct Answer: (A) 6.0 fm

Solution:

Concept:

- The empirical nuclear radius relation is $R = R_0 A^{1/3}$, where A is the mass number and $R_0 \simeq 1.2$ fm.
- A femtometre is $1 \text{ fm} = 10^{-15} \text{ m}$. Nuclear volume is proportional to A , so radius depends on its cube root.

Step 1: Take the cube root of the mass number The given mass number is $A = 125 = 5^3$. Therefore $A^{1/3} = 5$. The radius must be five times the radius constant, rather than 125 times that constant.

Step 2: Substitute in the radius relation Using $R_0 = 1.2$ fm,

$$R = (1.2 \text{ fm}) \times 5 = 6.0 \text{ fm}.$$

Option (B), 30 fm, would result from using $A^{2/3} = 25$ instead of $A^{1/3}$. Option (D), 150 fm, incorrectly uses $R \propto A$. Option (C), 72 fm, also does not follow the nuclear radius relation.

Step 3: Conclusion The nuclear radius is $6.0 \text{ fm} = 6.0 \times 10^{-15} \text{ m}$. Hence, the correct option is (A).

Quick Tip to Solve: Recognise $125 = 5^3$ immediately and multiply 1.2 fm by 5; do not multiply the radius constant by the mass number itself.

13. Assertion (A): In Young's double-slit experiment, the fringe width for dark and bright fringes is the same.

Reason (R): Fringe width is given by $\beta = \frac{\lambda D}{d}$, where symbols have their usual meanings.

Select the correct answer from the codes given below:

[1 mark]

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

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

Solution:

Concept:

- In Young's double-slit experiment, fringe width is the distance between successive bright fringes or between successive dark fringes.
- For wavelength λ , screen distance D and slit separation d , the fringe width is $\beta = \lambda D/d$, in the usual small-angle approximation.

Step 1: Evaluate the assertion Bright fringes occur at $y_n = n\lambda D/d$, whereas dark fringes occur at $y_n = (n + 1/2)\lambda D/d$. Increasing n by one changes either position by $\lambda D/d$. The spacing of successive bright fringes therefore equals that of successive dark fringes, so Assertion (A) is true.

Step 2: Evaluate the reason Reason (R) states the correct expression $\beta = \lambda D/d$. It applies to both sequences of fringes; their positions differ by half a fringe width, but their widths are the same. Thus Reason (R) is also true.

Step 3: Check the explanatory link The common formula depends on the same wavelength, screen distance and slit separation for both types of fringes. This directly explains the equal widths asserted in (A). Option (B) misses this link, while (C) and (D) incorrectly classify one or both true statements 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: Distinguish fringe width from bright-to-adjacent-dark spacing: the former is β , whereas the latter is $\beta/2$.

14. Assertion (A): Energy is released when heavy nuclei undergo fission or light nuclei undergo fusion.
Reason (R): For heavy nuclei, binding energy per nucleon increases with increasing Z while for light nuclei, it decreases with increasing Z .

Select the correct answer from the codes given below:

[1 mark]

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

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

Solution:

Concept:

- Binding energy per nucleon measures the average energy required to separate a nucleus into free nucleons; a larger value corresponds to greater nuclear stability.
- Energy is released when a nuclear reaction increases the total binding energy. The binding-energy-per-nucleon curve rises through the light-nucleus region, reaches a maximum near iron and nickel, and falls gradually for heavy nuclei.

Step 1: Evaluate the assertion Heavy-nucleus fission produces medium-mass nuclei with higher binding energy per nucleon. Fusion of suitable light nuclei likewise forms more tightly bound nuclei. In both cases the products have greater total binding energy and less total rest mass, so the difference is released as energy. Assertion (A) is true.

Step 2: Evaluate the reason Reason (R) reverses the broad trend of the binding-energy-per-nucleon curve. In the light-nucleus region, binding energy per nucleon generally increases as nuclear size and Z increase; in the heavy-nucleus region, it generally decreases. Therefore the printed reason is false.

Step 3: Check the explanatory relation Energy release is explained by the increase in binding energy

of the products, not by the reversed trends stated in (R). Options (A) and (B) wrongly call the reason true, while (D) wrongly calls the assertion false. The appropriate code must classify the assertion as true and the reason as false.

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

Quick Tip to Solve: Locate the binding-energy peak near iron: light nuclei move towards it by fusion and heavy nuclei by fission, releasing energy.

15. Assertion (A): Photoelectric effect is a spontaneous phenomenon.

Reason (R): According to the wave picture of radiation, an electron would take hours/days to absorb sufficient energy to overcome the work function and come out from a metal surface.

Select the correct answer from the codes given below:

[1 mark]

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

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

Solution:

Concept:

- In photoelectric emission, an electron absorbs a photon of energy $h\nu$; emission is possible when $h\nu \geq \phi$, where ϕ is the metal's work function.
- The observed emission begins essentially immediately after suitable light reaches the surface. The classical wave model instead predicts gradual energy accumulation at sufficiently low intensity.

Step 1: Evaluate the assertion Here the printed word “spontaneous” refers to the prompt, practically instantaneous onset of photoelectric emission under suitable illumination. In this intended sense, A is true. It does not mean that a metal emits photoelectrons without incident radiation; the threshold-frequency condition must still be met.

Step 2: Evaluate the reason According to the classical wave picture, the incident energy is spread continuously over the wavefront. At low intensity an electron would need a long time, even hours or days in the corresponding classical estimate, to collect enough energy to escape. R correctly states this unsuccessful prediction of the wave model, so R is true.

Step 3: Test the explanatory connection A prediction of delayed emission cannot explain the observed immediate emission. The immediate transfer of a photon's energy explains that observation. Thus option (A) fails the explanation test, while (C) and (D) incorrectly declare R false.

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

Quick Tip to Solve: Separate an observed feature from a failed classical prediction: a predicted delay cannot explain instantaneous photoelectric emission.

16. Assertion (A): Induced emf produced in a coil will be more when the magnetic flux linked with the coil is more.

Reason (R): Induced emf produced is directly proportional to the magnetic flux.

Select the correct answer from the codes given below:

[1 mark]

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

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

Solution:

Concept:

- Faraday's law gives $\mathcal{E} = -N d\Phi/dt$, where N is the number of turns and Φ is the magnetic flux through one turn.
- The magnitude of induced emf depends on the rate of change of flux linkage, not on the instantaneous amount of linked flux.

Step 1: Evaluate the assertion A greater linked flux does not by itself imply a greater induced emf. For example, a coil in a strong but steady magnetic field with fixed area and orientation can have large flux and zero emf, because $d\Phi/dt = 0$. A smaller flux changing rapidly can produce a nonzero emf. Therefore A is false.

Step 2: Evaluate the reason R states proportionality to flux itself, whereas Faraday's law states proportionality to its time derivative. Multiplying a constant flux by any factor still gives zero induced emf. Therefore R is also false.

Step 3: Match the assertion-reason code Since neither statement correctly identifies the governing quantity, R cannot explain A. Options (A), (B) and (C) all require A to be true and are ruled out; (A) and (B) also incorrectly accept R.

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

Quick Tip to Solve: Whenever induced emf is compared, compare $|d\Phi/dt|$, not the size of Φ ; large constant flux induces no emf.

Section B (10 marks)

17. A light copper ring is freely suspended by a light string. A bar magnet is held horizontally with its length along the axis of the ring. The magnet is moved towards the ring with its N pole facing the loop. What will happen to the ring and its position ? Explain. [2 marks]

Solution:

Concept:

- Faraday's law, $\mathcal{E} = -d\Phi_B/dt$, gives an induced emf when the magnetic flux Φ_B through a conducting ring changes.
- Lenz's law fixes the induced current's direction: its magnetic effect opposes the change of flux that produces it.

Step 1: Identify the changing flux As the north pole approaches the copper ring along its axis, the magnet's field through the ring becomes stronger. Consequently, the linked magnetic flux increases. Copper provides a closed conducting path, so this changing flux induces an emf and a current in the ring even though no battery is connected.

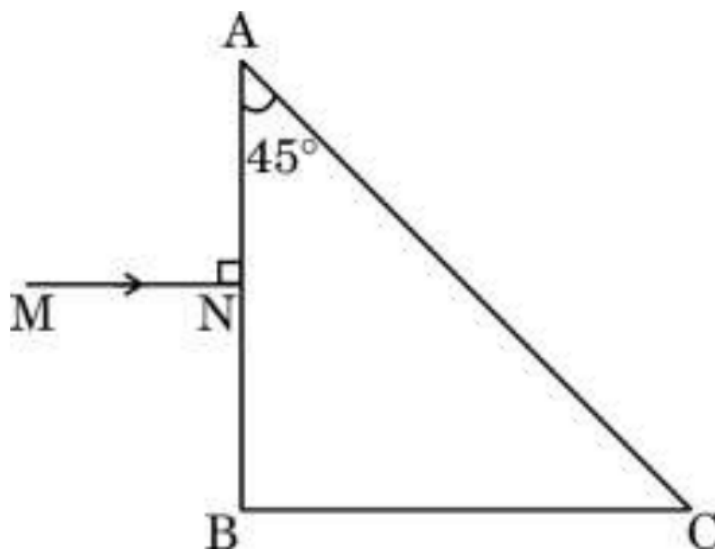
Step 2: Determine the induced polarity The ring's induced magnetic field opposes the increase in the approaching magnet's flux. Its face towards the magnet therefore acts as a north pole. By the right-hand rule, the induced current is anticlockwise when the ring is viewed from the approaching magnet's side. This induced polarity depends on the magnet's motion, rather than being permanent magnetisation of copper.

Step 3: Determine the ring's displacement The facing north poles repel. The light suspended ring is pushed away from the advancing magnet, along the magnet's axis, and the string deflects from its initial vertical position. If the relative motion stops, the changing-flux cause disappears and the induced current decays; the ring has no lasting repulsive force from this mechanism.

Step 4: Conclusion The ring is repelled and moves away from the approaching north pole. Its near face becomes a north pole by Lenz's law, so its initial suspended position changes.

Quick Tip to Solve: For an approaching pole, give the near face of a closed conducting ring the same pole: the induced repulsion opposes the approach.

18. A ray of light MN is incident normally on the face corresponding with side AB of a prism with an isosceles right-angled triangular base ABC. Trace the path of the ray as it passes through the prism when the refractive index of the prism material is (i) $\sqrt{2}$, and (ii) $\sqrt{3}$. [2 marks]



Solution:

Concept:

- At normal incidence a ray enters without deviation. In a right isosceles prism, the angle between the incident ray and the normal to hypotenuse AC is 45° .
- For a prism-to-air boundary, the critical angle C_r satisfies $\sin C_r = 1/\mu$. At $i = C_r$, refraction is grazing; at $i > C_r$, total internal reflection occurs.

Step 1: Trace the ray to the hypotenuse The ray MN is perpendicular to AB, so it passes straight into the prism at N. Let P be the point where it meets AC. Since AC makes 45° with AB and BC, the angle of incidence at P, measured from the normal to AC, is $i = 45^\circ$.

Step 2: Trace the ray for the first refractive index For $\mu = \sqrt{2}$, the critical angle is

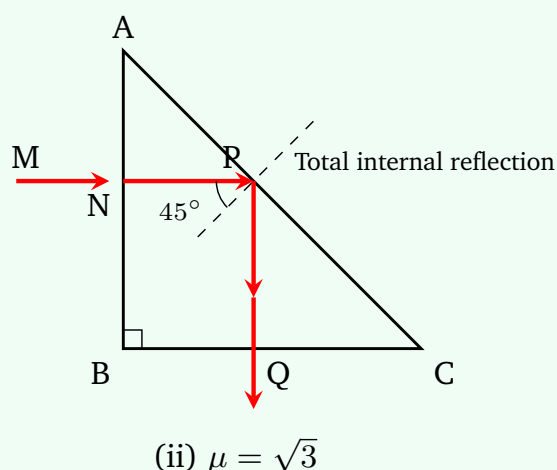
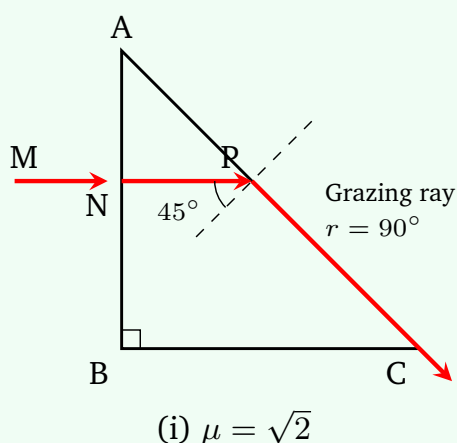
$$C_r = \sin^{-1}\left(\frac{1}{\sqrt{2}}\right) = 45^\circ.$$

Thus the incidence angle equals the critical angle. Snell's law gives $\sin r = \sqrt{2} \sin 45^\circ = 1$, so $r = 90^\circ$. The emergent ray therefore grazes along AC towards C; it is not the total-internal-reflection case.

Step 3: Trace the ray for the second refractive index For $\mu = \sqrt{3}$,

$$C_r = \sin^{-1}\left(\frac{1}{\sqrt{3}}\right) \simeq 35.3^\circ.$$

Since $45^\circ > C_r$, the ray undergoes total internal reflection at AC. The reflected ray travels vertically downwards to Q on BC. It strikes BC normally and emerges straight into air, without further deviation. Its final direction is perpendicular to its original direction.



Ray paths in air: grazing emergence for $\mu = \sqrt{2}$ and total internal reflection for $\mu = \sqrt{3}$. Dashed lines are normals at P.

Step 4: Conclusion For (i) $\sqrt{2}$, the ray emerges grazing along AC towards C. For (ii) $\sqrt{3}$, it reflects totally at AC and then emerges normally through BC, with a net deviation of 90° .

Quick Tip to Solve: Normal entry fixes the internal incidence at 45° ; compare this with the critical angle before drawing the ray at AC.

19. When monochromatic light is incident on a surface separating two media, the refracted and reflected light both have the same frequency as the incident frequency but the wavelength of refracted light is different. Explain why. [2 marks]

Solution:

Concept:

- The frequency ν of a light wave is fixed by the oscillating source. At a stationary boundary, the reflected and transmitted disturbances oscillate with the incident frequency.
- Wave speed and wavelength obey $v = \nu\lambda$. In a medium of refractive index n , the phase speed is $v = c/n$, where c is the speed of light in vacuum.

Step 1: Explain why the frequencies remain equal At the boundary, the incident light drives the charges in the material to oscillate at its own frequency. These oscillations produce the reflected and refracted waves. For the usual stationary interface and linear optical response, the boundary cannot create a different oscillation rate, so

$$\nu_{\text{incident}} = \nu_{\text{reflected}} = \nu_{\text{refracted}} = \nu.$$

The wave's time period therefore remains unchanged in reflection and refraction.

Step 2: Relate the changed speed to the wavelength The refracted wave travels in the second medium, where its speed differs from that in the first medium. Because the frequency remains fixed, its wavelength changes in the same ratio as its speed:

$$\lambda_1 = \frac{c}{n_1\nu}, \quad \lambda_2 = \frac{c}{n_2\nu}, \quad \frac{\lambda_2}{\lambda_1} = \frac{n_1}{n_2}.$$

Thus entry into a higher-index medium decreases both speed and wavelength. The reflected wave remains in the original medium, so its speed and wavelength remain the same as those of the incident wave.

Step 3: Conclusion Reflection and refraction preserve frequency at a stationary boundary. Refraction changes the propagation speed, and hence the wavelength, according to $\lambda = v/\nu$.

Quick Tip to Solve: Keep frequency fixed at an interface, then scale wavelength with speed: a larger refractive index means a smaller wavelength.

20. Suppose a pure Si crystal has 5×10^{28} atoms per m^3 . It is doped with 5×10^{22} atoms per m^3 of Arsenic. Calculate the majority and minority carrier concentration in the doped silicon. (Given: $n_i = 1.5 \times 10^{16} \text{ m}^{-3}$) [2 marks]

Solution:

Concept:

- Arsenic is a pentavalent donor impurity. Each ionised donor supplies one conduction electron, making the silicon an n-type semiconductor with electrons as majority carriers.
- At thermal equilibrium, the electron concentration n and hole concentration p obey the mass-action law $np = n_i^2$, where n_i is the intrinsic carrier concentration at the same temperature.

Step 1: Identify the majority carriers and their concentration The donor concentration is $N_D = 5 \times 10^{22} \text{ m}^{-3}$, much larger than $n_i = 1.5 \times 10^{16} \text{ m}^{-3}$. Assuming complete donor ionisation, as usual for this calculation, the thermally generated electrons make a negligible contribution compared with donor electrons. Hence,

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

The silicon atom density counts lattice atoms, not free electrons. The stated doping corresponds to one donor per million silicon atoms, so it is the donor density that determines the majority carrier concentration.

Step 2: Apply the mass-action law to the minority carriers Holes are the minority carriers. Using the intrinsic concentration supplied in the question,

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

The resulting hole density is much smaller than the electron density, consistent with n-type doping.

Step 3: Conclusion The majority carriers are electrons with $n \simeq 5 \times 10^{22} \text{ m}^{-3}$, and the minority carriers are holes with $p \simeq 4.5 \times 10^9 \text{ m}^{-3}$.

Quick Tip to Solve: For pentavalent doping with $N_D \gg n_i$, use $n \simeq N_D$ first and then $p = n_i^2/N_D$; do not use the silicon lattice atom density as a carrier density.

21(a). An electric iron rated 2.2 kW, 220 V is operated at 110 V supply. Find:

(i) its resistance, and

(ii) heat produced by it in 10 minutes.

[2 marks]

Solution:

Concept:

- For a resistive appliance, electrical power is $P = V^2/R$, where V is the potential difference and R is its resistance. The rated voltage and rated power determine its resistance.
- Joule's law gives the heat produced in time t as $H = Pt = V^2t/R$. Assume that the iron's resistance remains unchanged when it is connected to the lower supply voltage.

Step 1: Calculate the resistance from the ratings The rating means the iron consumes 2.2 kW = 2200 W when connected to 220 V. Therefore,

$$R = \frac{V_{\text{rated}}^2}{P_{\text{rated}}} = \frac{(220)^2}{2200} = 22 \Omega.$$

Use the rated voltage here because the stated power belongs to the rated operating condition. The power drawn at the new voltage must be calculated separately.

Step 2: Find the heating at the actual supply voltage On the 110 V supply, the power is

$$P' = \frac{(110)^2}{22} = 550 \text{ W}.$$

Convert the heating time to seconds: $t = 10 \times 60 = 600$ s. The electrical energy converted into heat is then

$$H = P't = 550 \times 600 = 3.3 \times 10^5 \text{ J}.$$

Halving the voltage reduces the heating power to one quarter when the resistance is constant, agreeing with $550 \text{ W} = 2200 \text{ W}/4$.

Step 3: Conclusion (i) The resistance of the iron is 22Ω . (ii) The heat produced in 10 minutes at 110 V is 3.3×10^5 J, or 330 kJ.

Quick Tip to Solve: Find resistance using the rated pair first. At half the rated voltage, use one quarter of the rated power and convert minutes to seconds before calculating heat.

OR

21(b). A current of 4.0 A flows through a wire of length 1 m and cross-sectional area 1.0 mm^2 , when potential difference of 2 V is applied across its ends. Calculate the resistivity of the material of the wire.

[2 marks]

Solution:

Concept:

- Ohm's law relates the resistance R of the wire to the applied potential difference V and current I : $R = V/I$.
- For a uniform wire of length L and cross-sectional area A , $R = \rho L/A$, where ρ is the resistivity of the material. Thus $\rho = RA/L$, measured in $\Omega \text{ m}$.

Step 1: Calculate the resistance of the wire The applied potential difference is $V = 2\text{ V}$, and the resulting current is $I = 4.0\text{ A}$. The resistance of this particular wire is therefore

$$R = \frac{V}{I} = \frac{2}{4.0} = 0.50\ \Omega.$$

Resistance depends on the length and area of the specimen, whereas resistivity is a property of its material at a specified temperature.

Step 2: Convert the area and evaluate the resistivity The given area must be expressed in square metres. Since $1\text{ mm} = 10^{-3}\text{ m}$, squaring this conversion gives

$$A = 1.0\text{ mm}^2 = 1.0 \times 10^{-6}\text{ m}^2.$$

Substitute this area and $L = 1\text{ m}$ into the relation for resistivity:

$$\rho = \frac{RA}{L} = \frac{0.50 \times 1.0 \times 10^{-6}}{1} = 5.0 \times 10^{-7}\ \Omega\text{ m}.$$

The unit follows from resistance times area divided by length: $\Omega\text{ m}^2/\text{m} = \Omega\text{ m}$.

Step 3: Conclusion The resistivity of the wire material is $\rho = 5.0 \times 10^{-7}\ \Omega\text{ m}$.

Quick Tip to Solve: Use $\rho = VA/(IL)$ for a direct calculation, but first convert mm^2 to m^2 by multiplying by 10^{-6} .

Section C (21 marks)

22. What is meant by displacement current? A capacitor is being charged by a battery. Show that the Ampere-Maxwell law justifies the continuity and constancy of the current flowing in the circuit.

[3 marks]

Solution:

Concept:

- Displacement current is the current associated with a time-varying electric flux. In vacuum (approximately in air), it is $I_d = \epsilon_0 d\Phi_E/dt$, where Φ_E is electric flux and ϵ_0 is the permittivity of free space. It does not require charge transport across the capacitor gap.
- The Ampere-Maxwell law is $\oint_C \vec{B} \cdot d\vec{l} = \mu_0(I_c + I_d)$, where I_c is the conduction current and both currents are evaluated through a surface bounded by the same closed curve C .

Step 1: Express the changing electric flux between the plates Consider a parallel-plate capacitor with plate area A and instantaneous plate charges $+Q(t)$ and $-Q(t)$. Neglecting fringing, the field in the air gap is uniform and normal to the plates:

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

As the battery charges the capacitor, Q changes, so the electric flux through the gap changes even though no conduction charge crosses the insulating gap.

Step 2: Compare displacement current with the wire current The conduction current in a connecting wire is the rate at which charge reaches the plate, $I_c = dQ/dt$. Therefore, the displacement current in

the gap is

$$I_d = \varepsilon_0 \frac{d\Phi_E}{dt} = \varepsilon_0 \frac{d}{dt} \left(\frac{Q}{\varepsilon_0} \right) = \frac{dQ}{dt} = I_c.$$

Thus the current entering one plate has the same instantaneous magnitude as the displacement current through the gap and the conduction current leaving the other plate.

Step 3: Apply the law to two surfaces with the same boundary Choose a closed loop around a connecting wire. A surface bounded by this loop that cuts the wire carries conduction current $I_c = I$. A second surface with the same boundary can bulge between the capacitor plates; it has no conduction current, but carries displacement current $I_d = I$. In the usual ideal-capacitor treatment, the Ampere-Maxwell law gives the same result for either surface:

$$\oint_C \vec{B} \cdot d\vec{l} = \mu_0 I.$$

The displacement term removes the apparent interruption of current at the capacitor. Here constancy means the same total current at every cross-section at a given instant. It does not mean a constant current in time: the charging current generally decreases as the capacitor charges.

Step 4: Conclusion Displacement current is $I_d = \varepsilon_0 d\Phi_E/dt$. For the charging capacitor, $I_d = I_c = dQ/dt$, so the Ampere-Maxwell law ensures continuity and the same instantaneous current throughout the circuit, including the gap.

Quick Tip to Solve: Start with $\Phi_E = Q/\varepsilon_0$ for the capacitor gap and differentiate. The equality $I_d = dQ/dt = I_c$ proves current continuity immediately.

23. (a) Can a transformer step up or step down dc power supply?

(b) Can a step up transformer work as a step down transformer?

(c) Does a step up transformer contradict the principle of conservation of energy? Justify your answer. [3 marks]

Solution:

Concept:

- A transformer works by mutual induction: an alternating current in the input winding produces changing magnetic flux Φ in the core, inducing emf $\varepsilon = -N d\Phi/dt$ in a winding of N turns.
- For an ideal transformer, $V_s/V_p = N_s/N_p$ and $V_p I_p = V_s I_s$, where p and s denote the input and output windings and the voltages and currents are rms values.

Step 1: (a) Check whether dc produces changing flux With a steady dc supply, the current and hence the magnetic flux become constant after the switching transient. Therefore $d\Phi/dt = 0$, so there is no sustained induced emf in the secondary. A transformer cannot step up or step down a dc power supply. A brief emf at switching does not provide continuous transformed dc; the low resistance of the primary can also cause excessive current and heating.

Step 2: (b) Interchange the input and output windings Yes. In a step-up connection, the input is applied to the winding with fewer turns and the output is taken from the winding with more turns. If an appropriate ac input is applied to the winding with more turns and the output is taken from the

winding with fewer turns, their functions reverse. The new ratio is

$$\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{N_{\text{fewer}}}{N_{\text{more}}} < 1.$$

Thus it acts as a step-down transformer, provided the winding voltage and current ratings are respected.

Step 3: (c) Compare the input and output power In an ideal step-up transformer, the increased output voltage is accompanied by a decreased output current:

$$\frac{I_s}{I_p} = \frac{V_p}{V_s} = \frac{N_p}{N_s}.$$

Hence $V_s I_s = V_p I_p$: increasing voltage does not increase the available power. In a practical transformer, some input energy becomes heat through winding resistance and core losses, so the useful output power is smaller than the input power.

Step 4: Conclusion (a) No, steady dc cannot be transformed. (b) Yes, by interchanging the winding roles within their ratings. (c) No, a step-up transformer obeys energy conservation: higher voltage comes with lower current, and practical losses reduce output power.

Quick Tip to Solve: First check for changing flux; then use the turns ratio for voltage and its reciprocal for current. A higher voltage alone never implies higher power.

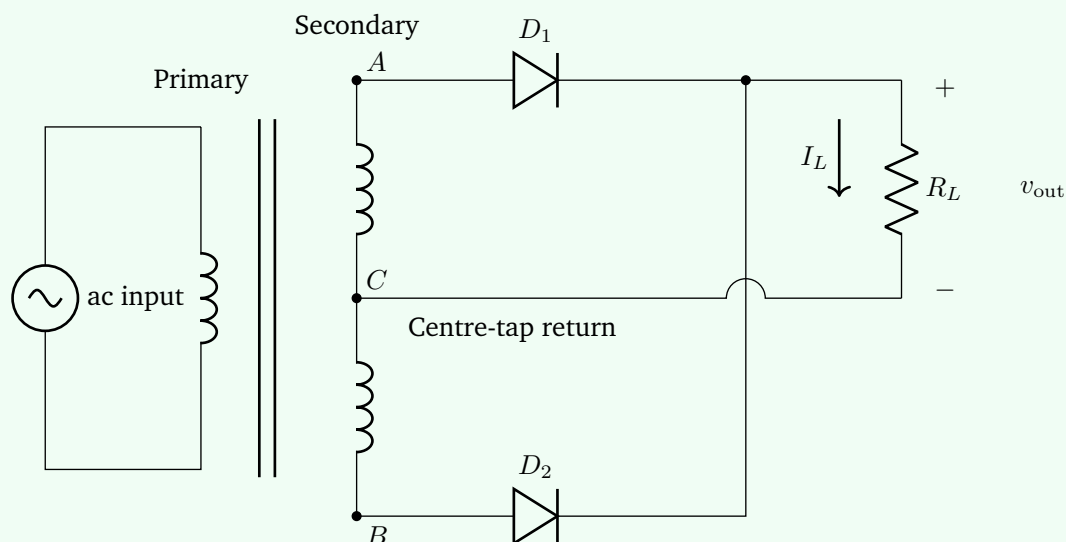
24. Draw a circuit diagram of a full-wave rectifier using p-n junction diodes. Explain its working and show the input-output waveforms. [3 marks]

Solution:

Concept:

- A p-n junction diode conducts appreciably when forward biased and blocks current when reverse biased. A rectifier uses this one-way conduction to obtain a unidirectional output from an alternating input.
- A centre-tapped transformer supplies two equal secondary voltages of opposite polarity relative to its centre tap C . Two diodes conduct on alternate half-cycles, maintaining the same direction of current through the load resistance R_L .

Step 1: Connect the two-diode rectifier Connect the anodes of diodes D_1 and D_2 to the secondary ends A and B . Join their cathodes at the positive output terminal and connect R_L between that terminal and the centre tap C . The transformer primary receives the ac input. The wire bridge in the diagram indicates a crossing without electrical contact.



Centre-tapped full-wave rectifier; the two diode cathodes join at the positive output.

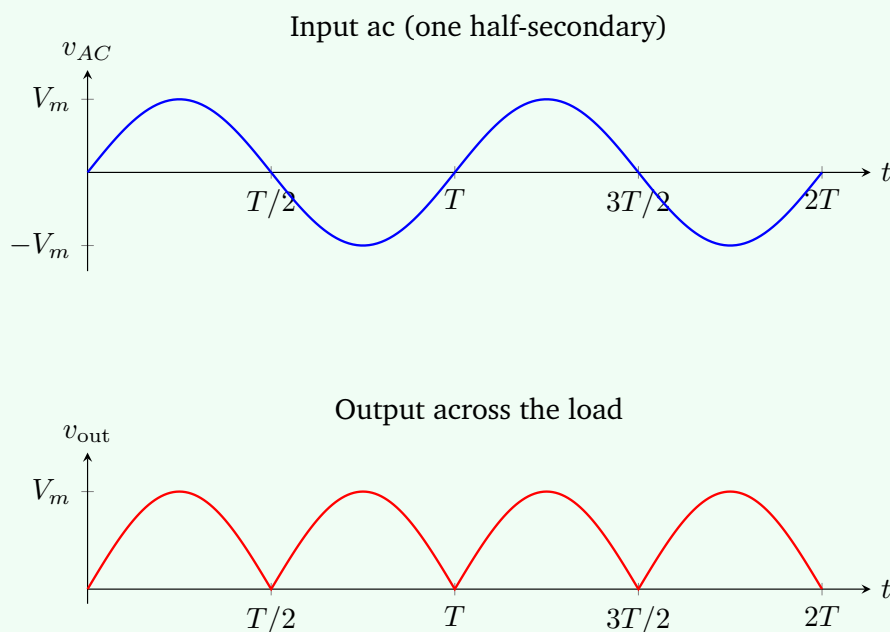
Step 2: Follow the positive half-cycle When A is positive relative to C , B is negative. Diode D_1 is forward biased and conducts, while D_2 is reverse biased and blocks. Conventional current follows $A \rightarrow D_1 \rightarrow R_L \rightarrow C$, returning through the upper half of the secondary. It flows downwards through R_L , making its upper terminal positive.

Step 3: Follow the negative half-cycle During the next half-cycle, B is positive and A is negative relative to C . Now D_2 conducts and D_1 blocks. The path is $B \rightarrow D_2 \rightarrow R_L \rightarrow C$, returning through the lower half of the secondary. Current again flows downwards through the load, so its polarity remains unchanged.

Step 4: Relate the input and output waveforms For ideal diodes, let the voltage of A relative to C be $v_{AC} = V_m \sin \omega t$. The other half-secondary voltage is $v_{BC} = -V_m \sin \omega t$. Whichever end is positive supplies the load, giving

$$v_{\text{out}} = V_m |\sin \omega t|.$$

The graph shows the ac waveform of one half-secondary and the load output. Both input half-cycles produce positive output pulses, so the output repeats after $T/2$ and its ripple frequency is $2f$, where $T = 1/f$. Real diode drops slightly reduce the peaks; without a filter the output is pulsating dc.



Ideal input and output waveforms; output pulses recur every half input period.

Step 5: Conclusion A centre-tapped transformer and two p-n junction diodes form a full-wave rectifier. The diodes conduct alternately, while load current has the same direction on both half-cycles. The output is pulsating dc with twice the input frequency.

Quick Tip to Solve: Mark the centre tap first and trace each conducting path through the load. Both paths must give the same load-current arrow; the negative input half-cycle becomes a positive output pulse.

25. Two point charges $q_1 = 2.5 \times 10^{-7} \text{ C}$ **and** $q_2 = -2.5 \times 10^{-7} \text{ C}$ **are located at points** $(0, 0, -15 \text{ cm})$ **and** $(0, 0, 15 \text{ cm})$ **respectively. Find:**

- (a) the electric dipole moment of the system, and
(b) the magnitude and direction of the electric field at the origin $(0, 0, 0)$.

[3 marks]

Solution:

Concept:

- The electric dipole moment is $\vec{p} = q(\vec{r}_+ - \vec{r}_-)$, where q is the positive charge magnitude. It points from the negative charge to the positive charge, and its magnitude is charge times separation.
- A point charge produces field magnitude $E = k|q|/r^2$, with $k = 1/(4\pi\epsilon_0)$. The field points away from a positive charge and towards a negative charge. The net field is the vector sum of the individual fields.

Step 1: (a) Identify the separation vector Choose $\hat{z}$ along the positive z -axis. The positive charge is at $z = -0.15 \text{ m}$ and the negative charge at $z = +0.15 \text{ m}$. The vector from the negative charge to the positive charge is

$$\vec{r}_+ - \vec{r}_- = (-0.15 - 0.15)\hat{z} = -0.30\hat{z} \text{ m.}$$

Therefore the dipole moment is

$$\vec{p} = (2.5 \times 10^{-7})(-0.30)\hat{z} = -7.5 \times 10^{-8}\hat{z} \text{ C m.}$$

Its magnitude uses the full charge separation, 30 cm, and its direction is the negative z -direction.

Step 2: (b) Determine both field directions at the origin The origin lies midway between the charges, 0.15 m from each. The field of the positive charge at $z = -0.15$ m points away from it, towards $+\hat{z}$. The field of the negative charge at $z = +0.15$ m points towards it, also towards $+\hat{z}$. Thus the equal field magnitudes add; they do not cancel even though the net charge is zero.

Step 3: Add the two Coulomb fields Using $k = 9 \times 10^9 \text{ N m}^2 \text{C}^{-2}$, the field magnitude due to either charge is

$$E_1 = E_2 = \frac{(9 \times 10^9)(2.5 \times 10^{-7})}{(0.15)^2} = 1.0 \times 10^5 \text{ N C}^{-1}.$$

Superposition gives

$$\vec{E}(0) = (E_1 + E_2)\hat{z} = 2.0 \times 10^5 \hat{z} \text{ N C}^{-1}.$$

Direct addition is appropriate because the origin is between the charges; a far-field axial dipole approximation cannot be used there.

Step 4: Conclusion (a) $\vec{p} = -7.5 \times 10^{-8} \hat{z} \text{ C m}$, directed from the negative charge to the positive charge. (b) $E = 2.0 \times 10^5 \text{ N C}^{-1}$, along the positive z -axis, opposite to the dipole moment.

Quick Tip to Solve: Use the full separation for dipole moment and the half-separation for each midpoint field. Between unlike charges, the electric fields point the same way and add.

26. Photoemission of electrons occurs from a metal ($\phi_0 = 1.96 \text{ eV}$) when light of frequency $6.4 \times 10^{14} \text{ Hz}$ is incident on it. Calculate:

- (a) Energy of a photon in the incident light,
- (b) The maximum kinetic energy of the emitted electrons, and
- (c) The stopping potential.

[3 marks]

Solution:

Concept:

- A photon of frequency ν carries energy $E = h\nu$, where h is Planck's constant.
- Einstein's photoelectric equation is $K_{\max} = h\nu - \phi_0$, where ϕ_0 is the work function, the minimum energy needed to liberate an electron.
- The stopping potential has magnitude $V_s = K_{\max}/e$, where e is the magnitude of the electron charge; $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$.

Step 1: (a) Calculate the incident photon energy Use the supplied value $h = 6.63 \times 10^{-34} \text{ J s}$ and the incident frequency $\nu = 6.4 \times 10^{14} \text{ Hz}$:

$$\begin{aligned} E &= h\nu = (6.63 \times 10^{-34})(6.4 \times 10^{14}) \\ &= 4.2432 \times 10^{-19} \text{ J}, \\ E &= \frac{4.2432 \times 10^{-19}}{1.6 \times 10^{-19}} \text{ eV} = 2.652 \text{ eV}. \end{aligned}$$

This exceeds the work function 1.96 eV, so the incident photons can cause photoemission.

Step 2: (b) Subtract the work function Each emitted electron uses part of the photon energy to escape from the metal. An electron that escapes without losing any additional energy has the maximum

kinetic energy:

$$\begin{aligned}K_{\max} &= E - \phi_0 = 2.652 - 1.96 \\&= 0.692 \text{ eV}, \\K_{\max} &= 0.692(1.6 \times 10^{-19}) = 1.1072 \times 10^{-19} \text{ J}.\end{aligned}$$

The subtraction uses energies expressed in the same unit. Electrons losing energy inside the metal emerge with kinetic energies below this maximum.

Step 3: (c) Find the retarding voltage At the stopping potential, the retarding electric field just prevents even the fastest photoelectrons from reaching the collector. Hence,

$$eV_s = K_{\max}, \quad V_s = \frac{1.1072 \times 10^{-19}}{1.6 \times 10^{-19}} = 0.692 \text{ V}.$$

This is the magnitude of the stopping potential; the collector is negative relative to the emitting surface.

Step 4: Conclusion (a) $E \approx 4.24 \times 10^{-19} \text{ J} = 2.65 \text{ eV}$; (b) $K_{\max} \approx 1.11 \times 10^{-19} \text{ J} = 0.692 \text{ eV}$; (c) $V_s = 0.692 \text{ V}$ in magnitude.

Quick Tip to Solve: Keep extra digits until subtracting the work function. Once $K_{\max}$ is in eV, its numerical value directly gives the stopping potential in volts.

27(a). (i) Write any two features of nuclear forces.

(ii) If both the number of protons and the neutrons are conserved in each nuclear reaction, in what way is mass converted into energy (or vice versa) in a nuclear reaction? Explain. [3 marks]

Solution:

Concept:

- Nuclear forces bind protons and neutrons, collectively called nucleons, inside a nucleus. Their behaviour is different from that of the long-range electrostatic force.
- Nuclear binding energy B is related to the mass defect by $B = \Delta m c^2$, where c is the speed of light.
- The energy released by a nuclear reaction is $Q = (M_i - M_f)c^2$, where M_i and M_f are the total rest masses of the initial and final particles.

Step 1: (i) State two features of nuclear forces **Short range:** The nuclear force is effective only over distances of the order of a few femtometres, with $1 \text{ fm} = 10^{-15} \text{ m}$. It becomes negligible when nucleons are separated by distances much larger than nuclear dimensions.

Approximate charge independence: After excluding the electrostatic interaction, the nuclear interaction between two protons, two neutrons, or a proton and a neutron is approximately the same for comparable states. Thus nuclear attraction does not arise from the electric charge of the nucleons.

Step 2: (ii) Relate nuclear mass to binding energy A bound nucleus has a smaller rest mass than its constituent free nucleons. For a nucleus containing Z protons and N neutrons,

$$M = Zm_p + Nm_n - \frac{B}{c^2},$$

where m_p and m_n are the free proton and neutron masses. Therefore, preserving the numbers of protons and neutrons does not require the total rest mass of the nuclei to remain unchanged: their binding energies can change when the nucleons rearrange.

Step 3: Compare the initial and final binding energies With the same total numbers of protons and neutrons on both sides, the free-nucleon mass terms cancel. If B_i and B_f denote the sums of the initial and final binding energies,

$$Q = (M_i - M_f)c^2 = B_f - B_i.$$

If the products are more tightly bound in total, then $B_f > B_i$ and $M_f < M_i$; the decrease in rest mass appears as kinetic energy of the products and/or emitted radiation. Conversely, forming less tightly bound products requires supplied energy and increases their total rest mass. In both directions, total mass-energy is conserved although rest mass alone need not be.

Step 4: Conclusion Nuclear forces are short-ranged and approximately charge-independent. Even when proton and neutron numbers are conserved, a change in total binding energy changes the total rest mass, with $Q = (M_i - M_f)c^2$.

Quick Tip to Solve: Keep nucleon counts separate from nuclear masses: unchanged counts cancel the free-nucleon terms, leaving the binding-energy difference as the reaction energy.

OR

27(b). (i) Draw the number of scattered particles versus the scattering angle graph for scattering of alpha particles by a thin foil. Write two important conclusions that can be drawn from this plot.

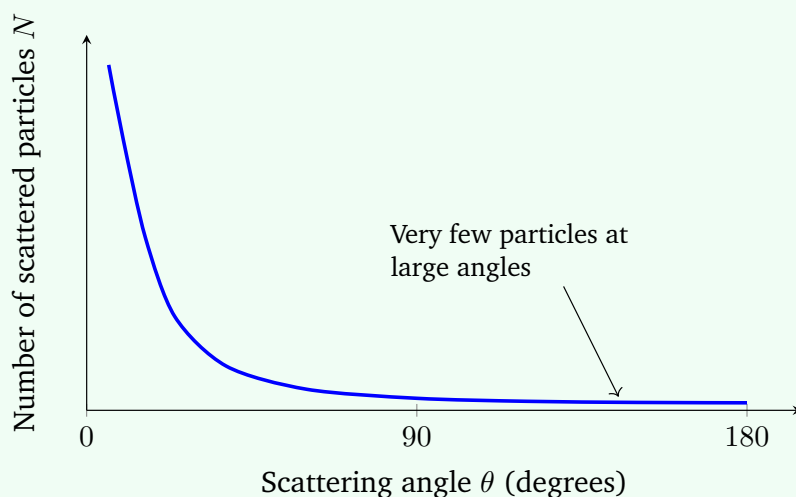
(ii) If Bohr's quantization postulate (angular momentum $= \frac{nh}{2\pi}$) is a basic law of nature, it should be equally valid for the case of planetary motion also. Why, then, do we never speak of quantization of orbits of planets around the Sun? Explain. [3 marks]

Solution:

Concept:

- In Rutherford scattering, most alpha particles pass through a thin foil with little deflection. For equal detector acceptance, the scattered count varies as $N(\theta) \propto 1/\sin^4(\theta/2)$, where θ is the scattering angle.
- Bohr's angular-momentum condition is $L = n\hbar$, with $\hbar = h/(2\pi)$ and positive integer n . Adjacent allowed values differ by $\Delta L = \hbar$.

Step 1: (i) Sketch the scattering distribution Plot the number N of detected scattered alpha particles vertically and their scattering angle θ horizontally, keeping the detector acceptance and the incident beam conditions fixed. The count is very large at small angles, falls rapidly as the angle increases, and is very small but nonzero at large angles, including backward scattering. The curve below shows this qualitative trend; its vertical scale is schematic.



Qualitative alpha-particle scattering distribution; vertical scale not to scale.

Step 2: Infer two properties of the atom **Most of an atom is empty space:** The predominance of particles with negligible or small deflection shows that most alpha particles traverse the atom without a close encounter with a concentrated charge.

The positive charge and almost all the mass occupy a tiny nucleus: The small number of large-angle and backward deflections requires a very strong repulsive interaction in a very small region. This is produced when a positively charged alpha particle passes close to a compact, positively charged, massive nucleus. The rarity of such deflections shows that the nucleus is much smaller than the atom.

Step 3: (ii) Compare orbital angular momentum with its quantum A planet has an enormous orbital angular momentum L because its mass and orbital dimensions are macroscopic. If the stated quantization condition is applied, its quantum number is therefore extremely large:

$$n = \frac{L}{\hbar} \gg 1, \quad \frac{\Delta L}{L} = \frac{\hbar}{L} = \frac{1}{n} \ll 1.$$

Thus adjacent allowed angular momenta differ by a completely negligible fraction of the planetary angular momentum. Corresponding allowed orbits are so closely spaced that their separation cannot be resolved in ordinary observations. The orbits consequently appear continuous, and classical mechanics is an excellent description; this does not require the quantum spacing to be exactly zero.

Step 4: Conclusion The sharply decreasing scattering curve shows that atoms are mostly empty space with a tiny, positively charged, massive nucleus. Planetary orbital quantization is unobservable because the relevant quantum numbers are immense and adjacent allowed orbits are exceedingly close.

Quick Tip to Solve: Link the many small-angle events to empty space and the rare backward events to the nucleus. For planets, compare $\hbar$ with L , rather than merely calling $\hbar$ small.

28. Write the expression for the magnetic field due to a current element in vector form. Consider a 1 cm segment of a wire, centered at the origin, carrying a current of 10 A in positive x -direction. Calculate the magnetic field $\vec{B}$ at a point (1 m, 1 m, 0). [3 marks]

Solution:

Concept:

- Biot–Savart law gives the magnetic field of a current element: $d\vec{B} = \frac{\mu_0}{4\pi} \frac{I d\vec{\ell} \times \hat{r}}{r^2} = \frac{\mu_0}{4\pi} \frac{I d\vec{\ell} \times \vec{r}}{r^3}$. Here $d\vec{\ell}$ points along the current, and $\vec{r}$ points from the element to the observation point.
- The magnetic field is perpendicular to both the current element and the displacement vector. Its direction follows the cross product, with $\hat{i} \times \hat{j} = \hat{k}$; in vacuum $\mu_0/(4\pi) = 10^{-7} \text{ T m A}^{-1}$.

Step 1: Identify the short current element and displacement The segment is centred at the origin and has length 1 cm = 10^{-2} m. Its current is directed along the positive x -axis. The displacement from its centre to the field point is therefore

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

Since the segment length is much smaller than its distance from the field point, use the short-current-element approximation, taking the displacement as that from the centre. This is the approximation appropriate to the supplied current-element question.

Step 2: Evaluate the cross product and substitute Only the transverse component of $\vec{r}$ contributes; its component parallel to the wire has zero cross product with $\Delta\vec{\ell}$:

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

Thus the direction is positive z , and substitution in Biot–Savart law gives

$$\begin{aligned} \vec{B} &\simeq 10^{-7} \frac{10 \times 10^{-2}}{(\sqrt{2})^3} \hat{k} \text{ T} \\ &= \frac{10^{-8}}{2\sqrt{2}} \hat{k} \text{ T} = 3.54 \times 10^{-9} \hat{k} \text{ T}. \end{aligned}$$

The r^3 denominator belongs to the form containing $\vec{r}$; using r^2 with this unnormalised displacement would give an incorrect result.

Step 3: Conclusion The vector law is $d\vec{B} = \frac{\mu_0 I}{4\pi} \frac{d\vec{\ell} \times \hat{r}}{r^2}$. For the given short segment, $\vec{B} \simeq 3.54 \times 10^{-9} \hat{k} \text{ T}$, directed along the positive z -axis.

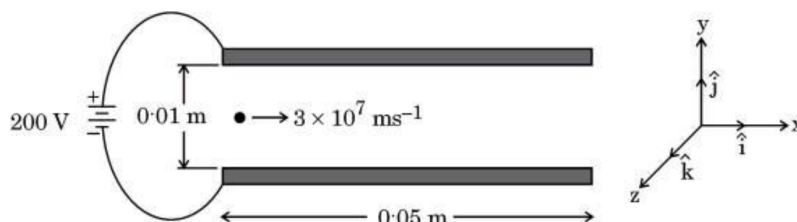
Quick Tip to Solve: For a wire along x , first take $\hat{i} \times (\hat{i} + \hat{j}) = \hat{k}$; then use $r^3 = (\sqrt{2})^3$ with the displacement-vector form.

Section D (8 marks)

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

29. The electric potential V and electric field E are closely related concepts in electrostatics. The electric field is a vector quantity that represents the force per unit charge at a given point in space, whereas electric potential is a scalar quantity that represents the potential energy per unit charge at a given point in space. Electric field and electric potential are related by the equations $E_r = -\frac{dV}{dr}$ and $\vec{E} = E_r \hat{r}$, i.e., electric field is the negative gradient of the electric potential. This means that electric field points in the direction of decreasing potential and its magnitude is the rate of change of potential with distance. The electric field is the force that drives a unit charge to move from higher potential region to lower potential region and electric potential difference between the two points determines the work done in moving a unit charge from one point to the other point.

A pair of square conducting plates having sides of length 0.05 m are arranged parallel to each other in x - y plane. They are 0.01 m apart along z -axis and are connected to a 200 V power supply as shown in the figure. An electron enters with a speed of $3 \times 10^7 \text{ m s}^{-1}$ horizontally and symmetrically in the space between the two plates. Neglect the effect of gravity on the electron. [4 marks]



29(i). The electric field $\vec{E}$ in the region between the plates is:

[1 mark]

- (A) $\left(2 \times 10^2 \frac{\text{V}}{\text{m}}\right) \hat{k}$
- (B) $-\left(2 \times 10^2 \frac{\text{V}}{\text{m}}\right) \hat{k}$
- (C) $\left(2 \times 10^4 \frac{\text{V}}{\text{m}}\right) \hat{k}$
- (D) $-\left(2 \times 10^4 \frac{\text{V}}{\text{m}}\right) \hat{k}$

Correct Answer: (C) $\left(2 \times 10^4 \frac{\text{V}}{\text{m}}\right) \hat{k}$

Solution:

Concept:

- Between parallel conducting plates, the uniform electric-field magnitude is $E = \Delta V/d$, where ΔV is the potential difference and d is the plate separation; edge effects are neglected.
- Electric field points from the positive plate to the negative plate, in the direction of decreasing potential. Its direction is independent of the sign of a test charge.

Step 1: Determine the field magnitude The applied voltage is 200 V, and the separation is 0.01 m, not the plate length 0.05 m. Therefore,

$$E = \frac{200}{0.01} = 2 \times 10^4 \text{ V m}^{-1}.$$

Options (A) and (B) have a magnitude smaller by a factor of one hundred.

Step 2: Determine the vector direction The upper plate is connected to the positive terminal and the lower plate to the negative terminal. The plates are separated along z , and the indicated positive z -sense is from the upper plate towards the lower plate. Thus the field is along $+\hat{k}$. Option (D) reverses this direction; the negative charge of the electron reverses its force, not the electric field.

Step 3: Conclusion $\vec{E} = (2 \times 10^4 \text{ V m}^{-1})\hat{k}$. Hence, the correct option is (C).

Quick Tip to Solve: Divide by the 0.01 m plate gap, then follow the battery polarity from the positive plate to the negative plate to set the sign of $\hat{k}$.

29(ii). In the region between the plates, the electron moves with an acceleration $\vec{a}$ given by: [1 mark]

(A) $-(3.5 \times 10^{15} \text{ ms}^{-2})\hat{k}$

(B) $(3.5 \times 10^{15} \text{ ms}^{-2})\hat{k}$

(C) $(3.5 \times 10^{13} \text{ ms}^{-2})\hat{i}$

(D) $-(3.5 \times 10^{13} \text{ ms}^{-2})\hat{i}$

Correct Answer: (A) $-(3.5 \times 10^{15} \text{ ms}^{-2})\hat{k}$

Solution:

Concept:

- The electric force on a charge is $\vec{F} = q\vec{E}$, so its acceleration is $\vec{a} = q\vec{E}/m$, with m the particle mass.
- An electron has charge $q = -e = -1.6 \times 10^{-19} \text{ C}$ and mass $m_e = 9.1 \times 10^{-31} \text{ kg}$. Its acceleration is opposite to the electric field, irrespective of its initial velocity.

Step 1: Obtain the electric field and force direction The upper plate is positive and the lower plate negative; the field follows the indicated positive z -sense. Hence

$$\vec{E} = \frac{200}{0.01} \hat{k} \text{ V m}^{-1} = 2 \times 10^4 \hat{k} \text{ V m}^{-1}.$$

The electron is attracted towards the upper, positive plate, so its acceleration has the direction $-\hat{k}$.

Step 2: Substitute the electron charge and mass Applying Newton's second law gives

$$\vec{a} = -\frac{(1.6 \times 10^{-19})(2 \times 10^4)}{9.1 \times 10^{-31}} \hat{k} = -3.52 \times 10^{15} \hat{k} \text{ m s}^{-2}.$$

Option (B) has the force direction appropriate to a positive charge. Options (C) and (D) incorrectly put the acceleration along the initial horizontal velocity and also give the wrong magnitude; the field has no x -component.

Step 3: Conclusion $\vec{a} \simeq -(3.5 \times 10^{15} \text{ m s}^{-2})\hat{k}$. Hence, the correct option is (A).

Quick Tip to Solve: First set the field direction from the plate polarity, then multiply by the electron's negative charge; do not use its horizontal velocity to choose the acceleration direction.

29(iii)(a). Time interval during which an electron moves through the region between the plates is: [1 mark]

- (A) $9.0 \times 10^{-9} \text{ s}$
- (B) $1.67 \times 10^{-8} \text{ s}$
- (C) $1.67 \times 10^{-9} \text{ s}$
- (D) $2.17 \times 10^{-9} \text{ s}$

Correct Answer: (C) $1.67 \times 10^{-9} \text{ s}$

Solution:

Concept:

- In a uniform electric field perpendicular to the initial velocity, the horizontal acceleration is zero. The horizontal speed u_x remains constant, so the transit time across plate length L is $t = L/u_x$.
- The electron starts midway between the plates with zero transverse velocity. Its transverse displacement is $s = \frac{1}{2}at^2$, which must remain below the half-gap $d/2$ for it to emerge without hitting a plate.

Step 1: Use the horizontal motion The field acts across the plate gap, not along the horizontal path. The electron therefore covers $L = 0.05 \text{ m}$ at the unchanged horizontal speed $3 \times 10^7 \text{ m s}^{-1}$:

$$t = \frac{0.05}{3 \times 10^7} = 1.67 \times 10^{-9} \text{ s}.$$

Option (B) is ten times too large; options (A) and (D) also do not equal length divided by horizontal speed.

Step 2: Check that the electron reaches the end The acceleration magnitude is $e(200/0.01)/m_e \simeq 3.52 \times 10^{15} \text{ m s}^{-2}$. During the transit, the transverse displacement is

$$s = \frac{1}{2}(3.52 \times 10^{15})(1.67 \times 10^{-9})^2 \simeq 4.9 \times 10^{-3} \text{ m}.$$

This is just below the half-gap 0.005 m , so no earlier collision shortens the calculated transit time. The increased total speed does not change the horizontal-speed calculation.

Step 3: Conclusion The time spent between the plates is $1.67 \times 10^{-9} \text{ s}$. Hence, the correct option is (C).

Quick Tip to Solve: Use the plate length 0.05 m for transit time, and reserve the plate gap 0.01 m for calculating the electric field.

29(iii)(b). The vertical displacement of the electron which travels through the region between the plates is: [1 mark]

- (A) 10 mm
- (B) 4.9 mm
- (C) 5.9 mm
- (D) 3.0 mm

Correct Answer: (B) 4.9 mm

Solution:

Concept:

- The horizontal speed remains constant because the electric force is perpendicular to it. The transit time is $t = L/u_x$, where L is the plate length and u_x is the initial speed.
- The transverse acceleration magnitude is $a = eE/m_e$, with $E = \Delta V/d$. The electron enters horizontally, so its initial transverse velocity is zero and its displacement magnitude is $s = \frac{1}{2}at^2$.

Step 1: Find the transit time and acceleration For plate length 0.05 m, gap 0.01 m and voltage 200 V,

$$t = \frac{0.05}{3 \times 10^7} = 1.667 \times 10^{-9} \text{ s},$$

$$a = \frac{(1.6 \times 10^{-19})(200/0.01)}{9.1 \times 10^{-31}} = 3.52 \times 10^{15} \text{ m s}^{-2}.$$

The acceleration is towards the positive, upper plate because the electron is negatively charged.

Step 2: Calculate the transverse displacement Using the zero initial transverse velocity gives

$$s = \frac{1}{2}(3.52 \times 10^{15})(1.667 \times 10^{-9})^2 = 4.89 \times 10^{-3} \text{ m} \simeq 4.9 \text{ mm}.$$

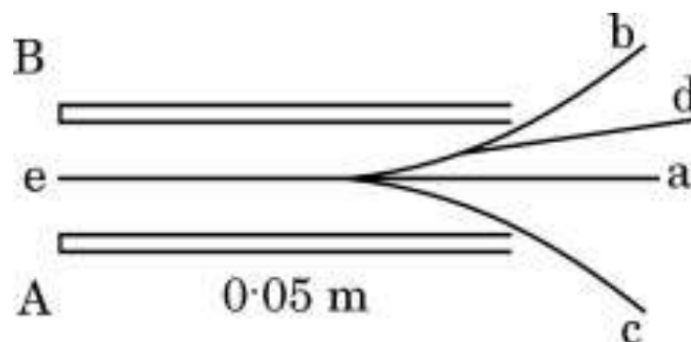
The result is below the 5 mm distance from the midpoint to a plate, so the electron emerges without striking it. Option (A), 10 mm, is the entire gap, not the displacement; (C) exceeds the available half-gap and (D) does not follow from the acceleration and transit time.

Step 3: Conclusion The electron is displaced by approximately 4.9 mm towards the positive plate. Hence, the correct option is (B).

Quick Tip to Solve: Calculate L/u_x first and square that time in $s = at^2/2$; compare the result with half the gap, since the electron enters midway between the plates.

29(iv). Which one of the following is the path traced by the electron in between the two plates?

[1 mark]



(A) a

(B) b

(C) c

(D) d

Correct Answer: (B) b

Solution:

Concept:

- An electron in a uniform electric field has constant acceleration opposite to the field. Thus it bends towards the positive plate.
- Uniform horizontal motion combined with uniformly accelerated transverse motion produces a parabola. With entry as origin, $x = u_x t$ and $z = \frac{1}{2} a_z t^2$, hence $z = a_z x^2 / (2u_x^2)$.

Step 1: Identify the direction of bending The battery connects the upper plate, labelled B in the path diagram, to its positive terminal. The electron has negative charge and is attracted towards this upper plate. Its initially horizontal path therefore bends upwards. Curve c bends towards the negative plate and cannot be the electron's path.

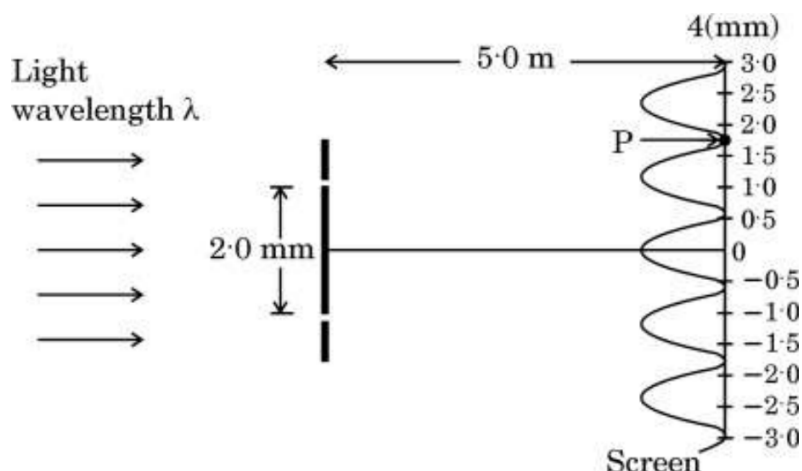
Step 2: Select the curve with the correct shape The horizontal speed stays constant while the upward transverse speed grows with time. Eliminating time gives a displacement proportional to x^2 , so the path is a parabola that begins with a horizontal tangent. The upward-curving path b has this behaviour. Path a would require no transverse force, while the straight inclined path d would require a constant transverse velocity instead of a growing one.

Step 3: Conclusion The electron follows the upward parabolic path b , towards the positive upper plate. Hence, the correct option is (B).

Quick Tip to Solve: Apply two checks to the drawn choices: a negative electron bends towards the positive plate, and constant transverse acceleration makes the path curved rather than straight.

30. In a Young's double-slit experiment, the two slits behave as coherent sources. When coherent light waves superpose over each other they create an interference pattern of successive bright and dark regions due to constructive and destructive interference.

Two slits 2 mm apart are illuminated by a source of monochromatic light and the interference pattern is observed on a screen 5.0 m away from the slits as shown in the figure. [4 marks]



30(i). What property of light does this interference experiment demonstrate? [1 mark]

- (A) Wave nature of light
- (B) Particle nature of light
- (C) Transverse nature of light
- (D) Both wave nature and transverse nature of light

Correct Answer: (A) Wave nature of light

Solution:

Concept:

- Interference is the redistribution of intensity when coherent waves superpose with a fixed phase difference.
- Both longitudinal and transverse waves can interfere; polarisation specifically demonstrates transverse nature.

Step 1: Identify the cause of the fringes The two coherent light waves reinforce at points of constructive interference and cancel at points of destructive interference. The resulting successive bright and dark fringes are therefore evidence of wave superposition.

Step 2: Distinguish wave behaviour from transverse character An interference experiment does not test the direction of vibration relative to propagation. Thus it cannot establish transverse nature, so options (C) and (D) add an unsupported claim. The observed interference also does not demonstrate particle nature, ruling out (B).

Step 3: Conclusion The experiment demonstrates the wave nature of light. Hence, the correct option is (A).

Quick Tip to Solve: Associate interference with wave nature and polarisation with transverse nature; they test different properties.

30(ii)(a). The wavelength of light used in this experiment is:

[1 mark]

- (A) 720 nm
- (B) 590 nm
- (C) 480 nm
- (D) 364 nm

Correct Answer: (C) 480 nm

Solution:

Concept:

- In Young's double-slit experiment, fringe width is $\beta = \lambda D/d$, where λ is wavelength, D is screen distance and d is slit separation.
- Fringe width is the distance between successive bright fringes, or between successive dark fringes.

Step 1: Read the fringe spacing from the figure The central bright fringe is at zero and the next bright fringes are at approximately 1.2 mm and 2.4 mm. Thus $\beta = 1.2$ mm. Use the spacing of equivalent fringes, not the separation of a neighbouring maximum and minimum.

Step 2: Calculate the wavelength With $d = 2.0 \times 10^{-3}$ m and $D = 5.0$ m,

$$\lambda = \frac{\beta d}{D} = \frac{(1.2 \times 10^{-3})(2.0 \times 10^{-3})}{5.0} = 4.8 \times 10^{-7} \text{ m.}$$

The wavelengths in options (A), (B) and (D) would give fringe widths of 1.80, 1.475 and 0.91 mm, respectively, which do not fit the plotted spacing.

Step 3: Conclusion The wavelength is 480 nm. Hence, the correct option is (C).

Quick Tip to Solve: Read one full bright-to-bright interval, then use $\lambda = \beta d/D$ with both millimetre lengths converted to metres.

OR

30(ii)(b). The fringe width in the interference pattern formed on the screen is:

[1 mark]

- (A) 1.2 mm
- (B) 0.2 mm
- (C) 4.2 mm
- (D) 6.8 mm

Correct Answer: (A) 1.2 mm

Solution:

Concept:

- Fringe width β is the separation between successive maxima or between successive minima in a Young's double-slit pattern.
- A bright fringe and its adjacent dark fringe are separated by $\beta/2$, so they must not be treated as successive equivalent fringes.

Step 1: Locate equivalent fringes in the plotted pattern The central maximum is at $y = 0$. The adjacent maxima are approximately at $y = \pm 1.2$ mm, with the next maxima at $y = \pm 2.4$ mm. The equally spaced minima are consistent with the same period.

Step 2: Measure one complete fringe interval Taking consecutive bright fringes on the positive side gives

$$\beta = y_2 - y_1 = (2.4 - 1.2) \text{ mm} = 1.2 \text{ mm}.$$

Option (B) is much smaller than the repeated fringe spacing; options (C) and (D) exceed several visible fringe intervals. None represents the separation between adjacent equivalent fringes.

Step 3: Conclusion The fringe width is 1.2 mm. Hence, the correct option is (A).

Quick Tip to Solve: Measure between two neighbouring peaks of the intensity curve, not between a peak and the nearest zero.

30(iii). The path difference between the two waves meeting at point P, where there is a minimum in the interference pattern is: [1 mark]

(A) $8.1 \times 10^{-7} \text{ m}$

(B) $7.2 \times 10^{-7} \text{ m}$

(C) $6.5 \times 10^{-7} \text{ m}$

(D) $6.0 \times 10^{-7} \text{ m}$

Correct Answer: (B) $7.2 \times 10^{-7} \text{ m}$

Solution:

Concept:

- At a screen coordinate y , the magnitude of the path difference is $\Delta \simeq dy/D$, where d is slit separation and D is screen distance.
- A dark fringe satisfies $\Delta = (2n - 1)\lambda/2$, with $n = 1, 2, \dots$ counted outward from the central bright fringe.

Step 1: Identify the minimum at P The first dark fringe above the central maximum lies near 0.6 mm. Point P is the second minimum, near $y_P = 1.8 \text{ mm}$, between the bright fringes at 1.2 mm and 2.4 mm.

Step 2: Calculate and check the path difference Substituting the screen coordinate and the given apparatus dimensions gives

$$\Delta = \frac{(2.0 \times 10^{-3})(1.8 \times 10^{-3})}{5.0} = 7.2 \times 10^{-7} \text{ m}.$$

This also equals $3\lambda/2$ for $\lambda = 480 \text{ nm}$, as required at the second minimum. The other options give $\Delta/\lambda = 1.6875$, approximately 1.354, and 1.25, none of which is an odd half-integer.

Step 3: Conclusion The path difference at P is $7.2 \times 10^{-7} \text{ m}$. Hence, the correct option is (B).

Quick Tip to Solve: Count dark fringes outward from the central maximum: the first has $\lambda/2$, while the second has $3\lambda/2$.

30(iv). When the experiment is performed in a liquid of refractive index greater than 1, then fringe pattern will: [1 mark]

- (A) disappear
- (B) become blurred
- (C) be widened
- (D) be compressed

Correct Answer: (D) be compressed

Solution:

Concept:

- In a liquid of refractive index μ , light's frequency stays fixed and its wavelength becomes $\lambda' = \lambda/\mu$.
- Fringe width is $\beta = \lambda D/d$, where D is screen distance and d is slit separation.

Step 1: Find the change in wavelength Since $\mu > 1$, uniform immersion reduces the wavelength from λ to λ/μ . The slit separation and screen distance remain fixed.

Step 2: Compare the fringe widths Substitution of the shorter wavelength gives

$$\beta' = \frac{\lambda' D}{d} = \frac{\lambda D}{\mu d} = \frac{\beta}{\mu} < \beta.$$

Adjacent fringes move closer together. Uniform immersion preserves coherence, ruling out disappearance or blurring in (A) and (B). Widening in (C) would require a longer wavelength, whereas the wavelength decreases here.

Step 3: Conclusion The fringe pattern is compressed. Hence, the correct option is (D).

Quick Tip to Solve: For uniform immersion with fixed geometry, divide fringe width by the refractive index.

Section E (15 marks)

31(a). (i) A parallel beam of monochromatic light falls normally on a single slit of width ' a ' and a diffraction pattern is observed on a screen placed at distance D from the slits. Explain:

- (I) the formation of maxima and minima in the diffraction pattern, and
- (II) why the maxima go on becoming weaker and weaker with its increasing number (n).

(ii) Write any two points of difference between interference pattern due to double-slit and diffraction pattern due to single-slit. [5 marks]

Solution:

Concept:

- By the Huygens-Fresnel principle, all parts of a uniformly illuminated slit act as coherent secondary sources. Their waves interfere at each point of the screen.
- For slit width a , wavelength λ and observation angle θ , the path difference between the two

extreme rays is $a \sin \theta$. For a distant screen, $y \simeq D\theta$, where y is measured from the centre and D is the screen distance.

- The single-slit intensity is $I = I_0(\sin \beta / \beta)^2$, where $\beta = \pi a \sin \theta / \lambda$ and I_0 is the central intensity.

Step 1: (i)(I) Explain the central maximum At the screen centre, $\theta = 0$, so light from every part of the slit travels the same optical distance. All secondary wavelets reach this point in phase; their amplitudes add constructively. This gives the brightest, central maximum. The intensity formula is understood by its limit $\sin \beta / \beta \rightarrow 1$ at $\beta = 0$.

Step 2: (i)(I) Obtain the minima by pairing wavelets For $a \sin \theta = \lambda$, divide the slit into two equal halves. Every wavelet in the upper half can be paired with a corresponding one a distance $a/2$ below it. The path difference within each pair is $(a/2) \sin \theta = \lambda/2$, so the pair cancels. Thus the resultant amplitude is zero and the first minimum forms. More generally, when $a \sin \theta = n\lambda$, divide the slit into $2n$ equal strips and pair neighbouring strips. Corresponding wavelets again differ in path by $\lambda/2$, giving complete cancellation. Hence the minima lie at

$$a \sin \theta_n = \pm n\lambda, \quad y_n \simeq \pm \frac{n\lambda D}{a}, \quad n = 1, 2, 3, \dots$$

The two first minima enclose the central bright band, whose width is $2\lambda D/a$.

Step 3: (i)(I) Explain the secondary maxima Between two successive minima, cancellation of the wavelets is incomplete. The resultant amplitude increases from zero, reaches a local maximum and falls back to zero, forming a secondary bright band. Its position is approximately

$$a \sin \theta \simeq \pm \left(n + \frac{1}{2}\right) \lambda, \quad n = 1, 2, 3, \dots$$

These are approximate positions: the exact noncentral maxima of the intensity expression obey $\tan \beta = \beta$. Thus secondary maxima occur between successive dark bands, symmetrically about the centre.

Step 4: (i)(II) Explain why successive maxima weaken At larger angles the phase changes more rapidly across the slit, so more of the slit contributions cancel one another. Only a smaller resultant amplitude remains. Quantitatively, $I/I_0 = \sin^2 \beta / \beta^2$: the numerator cannot exceed one, while the denominator grows with angle. At the exact secondary maxima, $\tan \beta = \beta$ gives

$$\frac{I_{\max}}{I_0} = \frac{1}{1 + \beta^2}.$$

Since $|\beta|$ increases with the order of the secondary maximum, its intensity decreases. The central maximum is therefore much stronger than the successive side maxima.

Step 5: (ii) State two differences between the patterns **Width:** In an ideal Young double-slit pattern with slit separation d , the bright and dark fringes are equally spaced, with fringe width $\lambda D/d$. In a single-slit diffraction pattern, the central bright band has width $2\lambda D/a$; each secondary bright band, measured between successive minima, has width $\lambda D/a$.

Intensity: For two equally illuminated, very narrow coherent slits, the interference maxima have equal intensity in the ideal model. In single-slit diffraction, the central maximum is brightest and

successive secondary maxima become weaker. Real finite-width double slits also produce a diffraction envelope, so the equal-intensity comparison assumes that envelope is negligible over the region considered.

Step 6: Conclusion Single-slit minima occur at $a \sin \theta = \pm n\lambda$ through complete pairwise cancellation; the central and secondary maxima arise from constructive addition and incomplete cancellation, respectively. Increasing cancellation makes higher-order maxima weaker. Compared with ideal double-slit interference, diffraction has a central bright band of twice the secondary-band width and unequal maximum intensities.

Quick Tip to Solve: Derive minima first by pairing equal slit strips; measure bright-band widths between adjacent minima. Treat the half-integer formula for secondary maxima as approximate.

OR

31(b). (i) With the help of a ray diagram, describe the construction and working of a compound microscope.

(ii) (I) The real image of an object placed between f and $2f$ from a convex lens can be seen on a screen placed at the image location. If the screen is removed, is the image still there? Explain.

(II) Plane and convex mirrors produce virtual images of objects. Can they produce real images under some circumstances? Explain. [5 marks]

Solution:

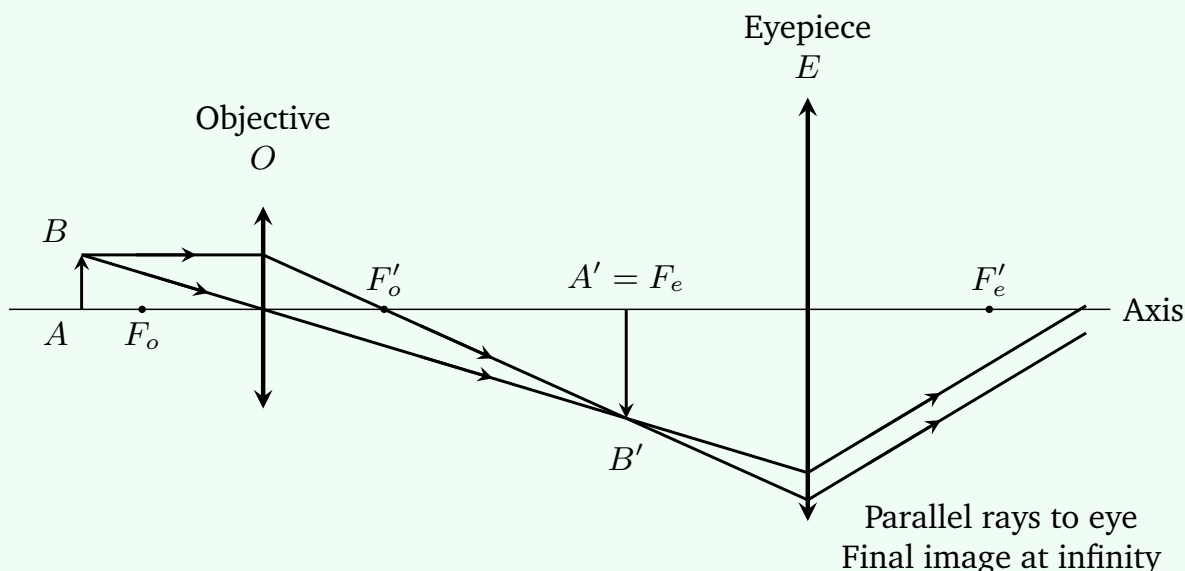
Concept:

- A compound microscope combines the linear magnification of a short-focal-length objective with the angular magnification of an eyepiece. The objective forms a real intermediate image, which acts as the object for the eyepiece.
- A real image is formed where light rays actually meet; a virtual image is formed where their extensions meet. A screen detects an image but does not cause its formation.
- The mirror formula is $1/f = 1/v + 1/u$, where f , v and u are the signed focal length, image distance and object distance. For light incident from the left, distances behind the mirror are positive.

Step 1: (i) Describe the construction A compound microscope consists of two convex lenses mounted coaxially at the ends of an adjustable tube. The objective, placed close to the object, has a very short focal length f_o and a small aperture. The eyepiece, placed close to the eye, has a focal length f_e larger than f_o and a larger aperture. The separation of the lenses is adjusted to focus the image clearly. The object is illuminated so that sufficient light enters the objective.

Step 2: (i) Trace the rays and explain the working Place a small object AB just beyond the first focus F_o of the objective. Since the object lies between f_o and $2f_o$, the objective forms a real, inverted and enlarged intermediate image $A'B'$ on the other side. In the ray diagram, one ray from B travels parallel to the principal axis and is refracted through F'_o ; the other passes undeviated through the optical centre of the objective. These rays meet at B' . For normal adjustment, arrange

$A'B'$ in the first focal plane of the eyepiece, with A' at F_e . The eyepiece acts as a magnifying glass. Rays from B' emerge parallel after refraction by the eyepiece, so the final image is virtual and at infinity. It is highly magnified and inverted relative to AB , and the eye views it without accommodation. Alternatively, placing $A'B'$ just inside the eyepiece's focal length produces the final virtual image at a finite distance, commonly the least distance of distinct vision. The diagram shows the normal-adjustment arrangement.



Compound microscope in normal adjustment: $A'B'$ lies in the eyepiece's front focal plane and the final virtual image is at infinity. Schematic ray diagram.

Step 3: (ii)(I) Explain what happens when the screen is removed Yes, the real image remains at the same location. The convex lens still refracts rays from each object point so that they converge at the corresponding image point beyond $2f$. Removing the screen changes neither the lens nor the ray paths. The screen merely scatters the light reaching it, making the image visible from many directions. Without a screen, an eye placed beyond the image within the emerging beam can receive the diverging rays after their crossing and see the image. An observer outside that beam need not see it.

Step 4: (ii)(II) Identify when plane and convex mirrors form real images Yes. Their usual virtual-image rule applies to real objects, which send diverging rays towards the mirror. If a converging beam falls on a mirror, the point behind the mirror at which the incident rays would have met acts as a virtual object. Reflection can then make the rays actually converge in front of the mirror. For a plane mirror, $f \rightarrow \infty$. If the converging beam would meet a distance $u > 0$ behind the mirror, then

$$\frac{1}{v} = -\frac{1}{u} \Rightarrow v = -u < 0.$$

The reflected rays therefore form a real image the same distance in front of the mirror. For a convex mirror, $f > 0$. A real image is obtained if the virtual object lies between the pole and the focus behind the mirror, so $0 < u < f$. In that case,

$$v = \frac{fu}{u - f} < 0.$$

Thus a sufficiently convergent incident beam produces a real image in front of a convex mirror. Such an incident beam can be supplied by a converging lens placed before the mirror.

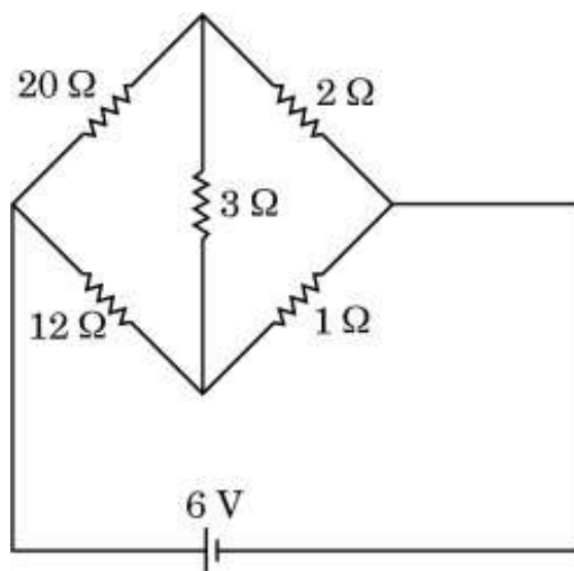
Step 5: Conclusion The objective forms an enlarged real intermediate image, and the eyepiece gives a further magnified virtual final image. A real lens image persists after its screen is removed. Both plane and convex mirrors can form real images for suitable virtual objects; for a convex mirror the virtual object must lie between its pole and focus.

Quick Tip to Solve: In the microscope sketch, first place the objective's real image at the eyepiece's front focus. For the mirror question, check whether the incident rays diverge from a real object or converge towards a virtual object.

32(a). (i) Derive the condition for which a Wheatstone Bridge is balanced.

(ii) Determine the current in $3\ \Omega$ branch of a Wheatstone Bridge in the circuit shown in the figure.

[5 marks]



Solution:

Concept:

- A Wheatstone bridge has four arms $AB = P$, $BC = Q$, $AD = R$ and $DC = S$, a galvanometer between B and D , and a source between A and C . Balance means zero current in the galvanometer.
- Kirchhoff's junction rule expresses charge conservation, and the potential drop across a resistor is IR . At balance, the two galvanometer junctions have equal potentials: $V_B = V_D$.

Step 1: (i) Compare the potential drops in the first pair of arms Let currents I_1 and I_2 flow along $A \rightarrow B \rightarrow C$ and $A \rightarrow D \rightarrow C$, respectively. When the galvanometer current is zero, the same current I_1 flows through P, Q , and the same current I_2 through R, S . Since $V_B = V_D$,

$$V_A - V_B = V_A - V_D \Rightarrow I_1 P = I_2 R.$$

Step 2: (i) Compare the second pair and eliminate the currents The drops from the equal-potential junctions to C also agree:

$$V_B - V_C = V_D - V_C \Rightarrow I_1 Q = I_2 S.$$

Dividing the two relations gives $P/Q = R/S$, or equivalently $PS = QR$. Conversely, this equality makes the potential-divider potentials at B and D equal, so no current flows through the connecting galvanometer. Thus it is the condition for a balanced bridge.

Step 3: (ii) Identify the nodes and test balance In the printed circuit, label the left, upper, right and lower vertices A, B, C, D , respectively. Thus $P = 20\ \Omega$, $Q = 2\ \Omega$, $R = 12\ \Omega$, $S = 1\ \Omega$, and $BD = 3\ \Omega$. Here $20/2 = 10$, whereas $12/1 = 12$; the bridge is unbalanced, so the central branch cannot be discarded. The longer battery plate is connected to A . Choose $V_C = 0$ and $V_A = 6\text{ V}$.

Step 4: (ii) Apply the junction rule at both central-branch endpoints Let the numerical values of V_B, V_D , in volts, be x, y . Summing currents leaving each junction gives

$$\begin{aligned}\frac{x-6}{20} + \frac{x}{2} + \frac{x-y}{3} &= 0, \\ \frac{y-6}{12} + y + \frac{y-x}{3} &= 0.\end{aligned}$$

Multiplication by 60 and 12, respectively, produces

$$53x - 20y = 18, \quad -4x + 17y = 6.$$

Eliminating x gives $821y = 390$. Substitution then gives $x = 426/821$. Hence the upper junction has the higher potential, and the central current is directed downwards.

Step 5: Conclusion (i) The balance condition is $P/Q = R/S$. (ii) The current through the $3\ \Omega$ branch is

$$I_{BD} = \frac{V_B - V_D}{3\ \Omega} = \frac{12}{821}\text{ A} \simeq 14.6\text{ mA},$$

flowing from the upper vertex to the lower vertex of the printed bridge.

Quick Tip to Solve: Test the arm ratios first; if they differ, keep the central resistor and solve for the two junction potentials using Kirchhoff's rule.

OR

32(b). (i) Consider a cylindrical conductor of length l and area of cross-section A . Current I is maintained in the conductor and electrons drift with velocity $\vec{v}_d$ $\left(|\vec{v}_d| = \frac{e|\vec{E}|}{m}\tau\right)$, (where symbols have their usual meanings). Show that the conductivity σ of the material of the conductor is given by $\sigma = \frac{ne^2\tau}{m}$.

(ii) The resistance of a metal wire at 20°C is $1.05\ \Omega$ and at 100°C is $1.38\ \Omega$. Determine the temperature coefficient of resistivity of this metal. [5 marks]

Solution:

Concept:

- For electron number density n , charge magnitude e , cross-sectional area A , and drift-speed magnitude v_d , the current magnitude is $I = neAv_d$. Conventional current is opposite to electron drift.
- Conductivity σ relates current density and electric field through $\vec{J} = \sigma\vec{E}$. The relaxation time τ is the mean time between successive electron collisions, and m is the electron mass.

- For a fixed wire, neglecting changes in its dimensions, $R = \rho l/A$; resistance and resistivity therefore have the same fractional temperature change. The linear approximation is $R_T = R_{T_0}[1 + \alpha_{T_0}(T - T_0)]$.

Step 1: (i) Obtain the current from the drifting electrons In a time interval Δt , electrons initially in a cylinder of length $v_d \Delta t$ pass a cross-section. Its volume is $Av_d \Delta t$, so the number passing is $nAv_d \Delta t$. The magnitude of transferred charge is $\Delta Q = neAv_d \Delta t$, giving

$$I = \frac{\Delta Q}{\Delta t} = neAv_d.$$

This uses the net drift superimposed on random thermal motion; the latter alone has no preferred direction and contributes no net current.

Step 2: (i) Insert the drift speed and identify conductivity Using the given $v_d = eE\tau/m$ and $J = I/A$,

$$J = nev_d = ne \left(\frac{eE\tau}{m} \right) = \frac{ne^2\tau}{m} E.$$

Electron drift is opposite to $\vec{E}$, but electrons have negative charge, so $\vec{J}$ is parallel to $\vec{E}$. Comparison with $J = \sigma E$ identifies the required conductivity. Equivalently, $E = V/l$ gives $I = (ne^2\tau/m)(A/l)V$, consistent with the wire's resistance $R = l/(\sigma A)$.

Step 3: (ii) Use the lower measured temperature as the reference Take $T_0 = 20^\circ\text{C}$, $R_{20} = 1.05 \Omega$, and $R_{100} = 1.38 \Omega$. The measured changes are

$$\Delta T = 100 - 20 = 80 \text{ K}, \quad \Delta R = 1.38 - 1.05 = 0.33 \Omega.$$

Rearranging the linear temperature relation yields

$$\begin{aligned} \alpha_{20} &= \frac{R_{100} - R_{20}}{R_{20}(100 - 20)} \\ &= \frac{0.33}{1.05 \times 80} \text{ K}^{-1} = 3.93 \times 10^{-3} \text{ K}^{-1}. \end{aligned}$$

The positive sign agrees with the observed increase in resistance of the metal. A temperature interval has the same numerical value in kelvin and degrees Celsius.

Step 4: Specify the reference of the temperature coefficient A fractional temperature coefficient depends on the reference resistance. The value above is referred to the supplied initial temperature, 20°C . If a coefficient referred specifically to 0°C is desired, the same straight-line data give $R_0 = 1.05 - 20(0.33/80) = 0.9675 \Omega$ and $\alpha_0 = (0.33/80)/0.9675 = 4.26 \times 10^{-3} \text{ K}^{-1}$. These values describe the same linear dependence with different reference temperatures.

Step 5: Conclusion (i) $\sigma = ne^2\tau/m$. (ii) With the given initial temperature 20°C as reference, the temperature coefficient of resistivity is $\alpha_{20} = 3.93 \times 10^{-3} \text{ K}^{-1}$.

Quick Tip to Solve: In the temperature formula, divide by the resistance at the chosen reference temperature; here the supplied initial resistance is at 20 degrees Celsius.

33(a). (i) A rectangular loop of sides a and b carrying current I is placed in a magnetic field $\vec{B}$ such that its area vector $\vec{A}$ makes an angle θ with $\vec{B}$. With the help of a suitable diagram, show that the torque $\vec{\tau}$ acting on the loop is given by $\vec{\tau} = \vec{m} \times \vec{B}$, where $\vec{m}(= I\vec{A})$ is the magnetic dipole moment of the loop.

(ii) A circular coil of 100 turns and radius $\left(\frac{10}{\sqrt{\pi}}\right)$ cm carrying current of 5.0 A is suspended vertically in a uniform horizontal magnetic field of 2.0 T. The field makes an angle 30° with the normal to the coil. Calculate:

(I) the magnetic dipole moment of the coil, and

(II) the magnitude of the counter torque that must be applied to prevent the coil from turning.

[5 marks]

Solution:

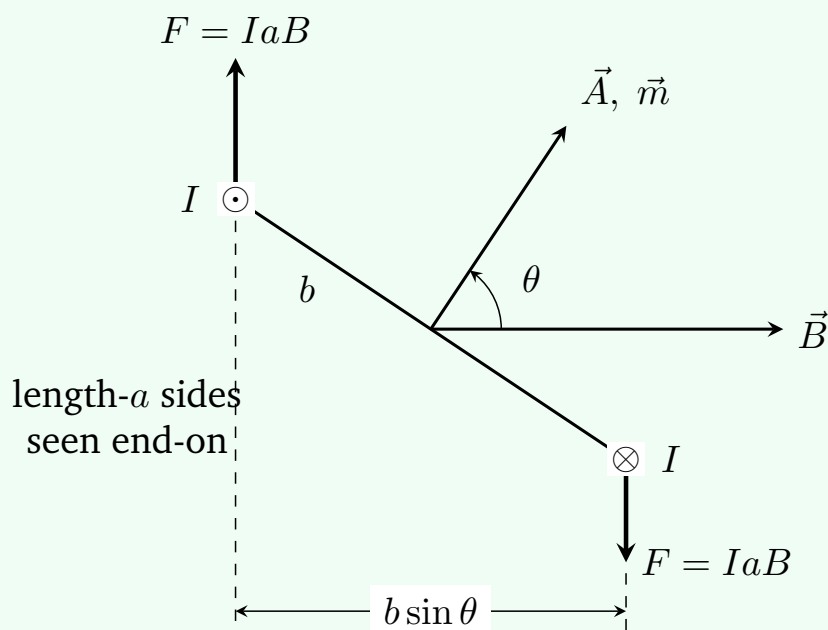
Concept:

- The magnetic force on a straight current-carrying side is $\vec{F} = I\vec{l} \times \vec{B}$, where $\vec{l}$ points along conventional current. A uniform field gives a closed loop zero net force but can exert a torque.
- The torque of a couple is one force multiplied by the perpendicular separation of the two lines of action. For a rectangular loop, $A = ab$, and its area-vector direction follows the right-hand rule for the current.
- The magnetic dipole moment is $\vec{m} = NI\vec{A}$ for a coil of N turns, reducing to $I\vec{A}$ for one turn. The angle used in magnetic torque is the angle between the field and the normal to the loop.

Step 1: (i) Choose the loop orientation and identify the force pair Let the two sides of length a be perpendicular to the plane containing $\vec{B}$ and the area vector $\vec{A}$. View these sides end-on, as in the diagram. The joining sides have length b , so that the normal makes angle θ with the field while a joining side makes the complementary angle with it. The two length- a sides carry opposite currents perpendicular to the field. Hence each experiences a force of magnitude

$$F = IaB.$$

Their forces are equal and opposite, as shown by the upward and downward arrows. These separated forces form the couple that turns the loop.



Edge-on view: the two sides of length a run perpendicular to the page. Dots and crosses indicate current out of and into the page.

Step 2: (i) Find the moment of the couple The distance between the two length- a sides is b , but the perpendicular separation of their force lines is its projection $b \sin \theta$. The other pair of sides experiences equal and opposite forces along the length- a direction; these forces are collinear and produce no resultant torque. Therefore the total torque magnitude is

$$\begin{aligned}\tau &= F(b \sin \theta) \\ &= (IaB)b \sin \theta \\ &= IAB \sin \theta.\end{aligned}$$

This also shows that the torque vanishes when the normal is parallel to the field and is greatest when the normal is perpendicular to it.

Step 3: (i) Express the torque as a vector Apply the right-hand rule to the circulating current to obtain $\vec{m} = I\vec{A}$. The force couple rotates this magnetic moment towards $\vec{B}$; its torque is perpendicular to the plane containing these two vectors, in the direction of $\vec{m} \times \vec{B}$. Since its magnitude is $mB \sin \theta$, the magnitude and direction together establish

$$\vec{\tau} = \vec{m} \times \vec{B}.$$

In the illustrated orientation the couple is clockwise, so the torque points into the page, consistently with this cross product.

Step 4: (ii) (I) Calculate the magnetic dipole moment of the coil Convert the radius to metres before computing area. With $N = 100$ and $I = 5.0 \text{ A}$,

$$\begin{aligned}r &= \frac{10}{\sqrt{\pi}} \text{ cm} = \frac{0.10}{\sqrt{\pi}} \text{ m}, \\ A &= \pi r^2 = \pi \frac{(0.10)^2}{\pi} = 0.010 \text{ m}^2, \\ m &= NIA = 100 \times 5.0 \times 0.010 = 5.0 \text{ A m}^2.\end{aligned}$$

The dipole moment is directed along the coil's normal, with its sense fixed by the current's right-hand rule.

Step 5: (ii)(II) Balance the magnetic torque The supplied 30° is already the angle between the normal and the horizontal field, so use it directly. For $B = 2.0 \text{ T}$,

$$\tau = mB \sin 30^\circ = 5.0 \times 2.0 \times \frac{1}{2} = 5.0 \text{ N m}.$$

To keep the suspended coil from turning, the applied counter torque must satisfy $\vec{\tau}_{\text{counter}} = -\vec{\tau}$. Thus it has the same magnitude as the magnetic torque and the opposite rotational sense.

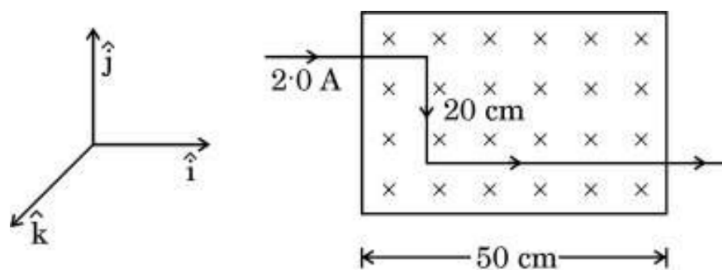
Step 6: Conclusion For one rectangular loop, $\vec{\tau} = \vec{m} \times \vec{B}$, with $\vec{m} = I\vec{A}$. For the given coil, $m = 5.0 \text{ A m}^2$ and the required counter-torque magnitude is 5.0 N m , opposing the magnetic torque.

Quick Tip to Solve: Use the angle to the coil's normal in $NIAB \sin \theta$. Here $r = 0.10/\sqrt{\pi} \text{ m}$ makes $\pi r^2 = 0.010 \text{ m}^2$, so π cancels before any numerical approximation.

OR

33(b). (i) Derive an expression for the force $\vec{F}$ acting on a conductor of length L and area of cross-section A carrying current I and placed in a magnetic field $\vec{B}$.

(ii) A part of a wire carrying 2.0 A current and bent at 90° at two points is placed in a region of uniform magnetic field $\vec{B} = -(0.50 \text{ T}) \hat{k}$, as shown in the figure. Calculate the magnitude of the net force acting on the wire. [5 marks]



Solution:

Concept:

- A charge q moving with velocity $\vec{v}$ in a magnetic field experiences the magnetic Lorentz force $\vec{f} = q\vec{v} \times \vec{B}$.
- For a conductor with electron number density n , electron charge magnitude e , cross-sectional area A and drift speed v_d , the conventional current is $I = neAv_d$.
- Forces on the parts of a bent wire add as vectors. In a uniform field, $\vec{F} = I \left(\int d\vec{l} \right) \times \vec{B}$, where $d\vec{l}$ points along the current and only wire portions within the field are included.

Step 1: (i) Count the moving charge carriers Consider a uniform straight conductor of length L and cross-sectional area A . Its volume is AL , so the number of free electrons in that length is $N_e = nAL$. Let $\hat{l}$ point along conventional current. The electrons drift opposite to this direction, with mean velocity $\vec{v}_d = -v_d \hat{l}$, and each has charge $-e$. Random thermal velocities average to zero, so it is the drift velocity that determines the resultant magnetic force.

Step 2: (i) Sum the magnetic forces and use the current relation The magnetic force on each drifting electron is

$$\vec{f} = (-e)(-v_d \hat{l}) \times \vec{B} = ev_d \hat{l} \times \vec{B}.$$

Adding over the nAL carriers gives the magnetic force transmitted to the conductor:

$$\begin{aligned}\vec{F} &= nALev_d \hat{l} \times \vec{B} \\ &= (neAv_d)L \hat{l} \times \vec{B} \\ &= I\vec{L} \times \vec{B}, \quad \vec{L} = L\hat{l}.\end{aligned}$$

Thus $F = ILB \sin \alpha$, where α is the angle between the conventional-current direction and the field. Its direction follows the cross product or Fleming's left-hand rule. The area A enters the carrier count, but disappears from the final expression because it is already included in $I = neAv_d$.

Step 3: (ii) Read the current path inside the field The field is $\vec{B} = -0.50\hat{k}$ T, into the plane of the figure. The two horizontal portions carry current to the right, and their combined length inside the field is the full region width, $50 \text{ cm} = 0.50 \text{ m}$. The connecting vertical portion carries current downward through $20 \text{ cm} = 0.20 \text{ m}$. Hence the net displacement from entry to exit, following current, is

$$\Delta\vec{r} = (0.50\hat{i} - 0.20\hat{j}) \text{ m}.$$

The portions outside the indicated field region experience no force from this field. The wire's total bent length must not be inserted as a scalar length, because forces on its perpendicular parts point in different directions.

Step 4: (ii) Add the forces as vectors Since the field is uniform, adding the three segment forces is equivalent to using the net displacement. With $I = 2.0 \text{ A}$, $\hat{i} \times \hat{k} = -\hat{j}$ and $\hat{j} \times \hat{k} = \hat{i}$,

$$\begin{aligned}\vec{F} &= I\Delta\vec{r} \times \vec{B} \\ &= 2.0(0.50\hat{i} - 0.20\hat{j}) \times (-0.50\hat{k}) \text{ N} \\ &= (0.20\hat{i} + 0.50\hat{j}) \text{ N}.\end{aligned}$$

The horizontal wire portions together give 0.50 N upward; the vertical portion gives 0.20 N to the right. As these two resultant components are perpendicular, the magnitude is

$$|\vec{F}| = \sqrt{(0.20)^2 + (0.50)^2} \text{ N} = \sqrt{0.29} \text{ N} \simeq 0.54 \text{ N}.$$

Step 5: Conclusion (i) The force on a straight conductor is $\vec{F} = I\vec{L} \times \vec{B}$, with $\vec{L}$ along conventional current. (ii) The bent wire experiences $\vec{F} = (0.20\hat{i} + 0.50\hat{j}) \text{ N}$, of magnitude 0.54 N .

Quick Tip to Solve: For a bent wire in a uniform magnetic field, use the displacement from the field-entry point to the field-exit point. Here the two rightward lengths add to 0.50 m , while the 0.20 m drop has a negative $\hat{j}$ sign.