

CBSE Class 12 Physics Question Paper 2026 with Solution PDF-Set 55/5/1



Question Paper with Solutions

Conducted by the Central Board of Secondary Education (CBSE)

Time Allowed: 3 hours

Maximum Marks: 70

General Instructions

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

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

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

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

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

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

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

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

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

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

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

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

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

Section A (16 marks)

1. Two small identical metallic balls having charges q and $-2q$ are kept far at a separation r . They are brought in contact and then separated at distance $\frac{r}{2}$. Compared to the initial force F , they will now: [1 mark]

- (A) attract with a force $\frac{F}{2}$
- (B) repel with a force $\frac{F}{2}$
- (C) repel with a force F
- (D) attract with a force F

Correct Answer: (B) repel with a force $\frac{F}{2}$

Solution:

Concept:

- Coulomb's law gives the force magnitude $F = k|q_1q_2|/r^2$, where $k = 1/(4\pi\epsilon_0)$ and r is the separation.
- Identical conducting balls share their total charge equally on contact. Like charges repel, while unlike charges attract.

Step 1: Find the charge on each ball after contact The total charge is conserved and equals $q - 2q = -q$. Since the balls are identical, each receives half of this charge:

$$q'_1 = q'_2 = -\frac{q}{2}.$$

Their charges now have the same sign, so the new force is repulsive. This eliminates the attractive-force options (A) and (D).

Step 2: Compare the force magnitudes Initially, the magnitude of the attractive force is

$$F = \frac{2kq^2}{r^2}.$$

With both the new charges and the new separation included, the force becomes

$$F' = \frac{k(q/2)^2}{(r/2)^2} = \frac{kq^2}{r^2} = \frac{F}{2}.$$

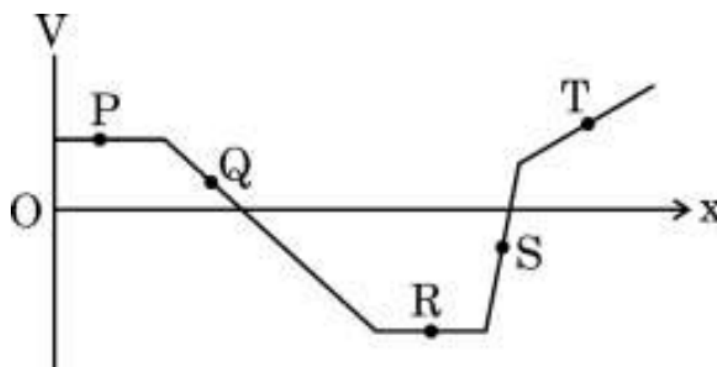
Option (C) overlooks the reduction in the product of the charges; halving the separation alone is not enough to determine the result.

Step 3: Conclusion The balls repel with a force $F/2$. Hence, the correct option is (B).

Quick Tip to Solve: After contact, conserve total charge first; then compare q_1q_2/r^2 using both the new charges and separation.

2. The figure represents the variation of the electric potential V at a point in a region of space as a function of its position along the x -axis. A charged particle will experience the maximum force at:

[1 mark]



- (A) P
- (B) Q
- (C) R
- (D) S

Correct Answer: (D) S

Solution:

Concept:

- The electric field along the x -axis is the negative potential gradient, $E_x = -dV/dx$.
- For a fixed particle charge q , the force magnitude is $|F_x| = |q| |dV/dx|$. The steepness of the graph, rather than the potential value, determines the force.

Step 1: Compare the potential gradients At P and R , the plotted potential is constant over a horizontal segment. Thus $dV/dx = 0$, and the electric force is zero at each of these points. Their nonzero potential values do not imply nonzero electric fields.

Step 2: Identify the steepest segment At Q , the graph slopes downwards, giving a nonzero field. At S , the upward segment is much steeper, so its slope has the largest absolute value among the four choices:

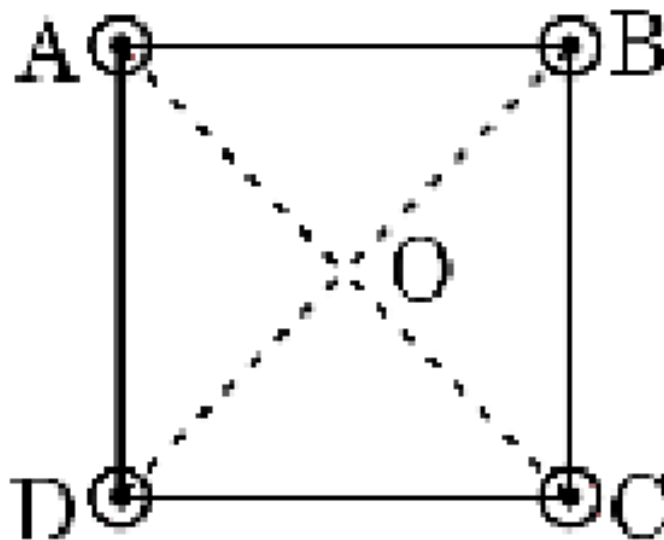
$$\left| \frac{dV}{dx} \right|_S > \left| \frac{dV}{dx} \right|_Q > \left| \frac{dV}{dx} \right|_P = \left| \frac{dV}{dx} \right|_R = 0.$$

The slope's sign sets the field direction; it does not change the comparison of force magnitudes. Hence options (A), (B) and (C) cannot give the greatest force.

Step 3: Conclusion The charged particle experiences the maximum force magnitude at S . Hence, the correct option is (D).

Quick Tip to Solve: On a potential-position graph, compare the absolute slopes; the highest or lowest potential need not give the strongest force.

3. Four long straight thin wires are held vertically at the corners A , B , C and D of a square of side ' a ', kept on a table and carry equal current ' I '. The wire at A carries current in upward direction whereas the current in the remaining wires flows in downward direction. The net magnetic field at the centre of the square will have the magnitude: [1 mark]



- (A) $\frac{\mu_0 I}{\pi a}$ and directed along OC
 (B) $\frac{\mu_0 I}{\pi a\sqrt{2}}$ and directed along OD
 (C) $\frac{\mu_0 I\sqrt{2}}{\pi a}$ and directed along OB
 (D) $\frac{2\mu_0 I}{\pi a}$ and directed along OA

Correct Answer: (C) $\frac{\mu_0 I\sqrt{2}}{\pi a}$ and directed along OB

Solution:

Concept:

- A long straight wire carrying current I produces a magnetic field $B = \mu_0 I / (2\pi d)$ at perpendicular distance d . Its direction follows the right-hand thumb rule.
- Magnetic fields add as vectors. For four equal currents in the same direction at the corners of a square, fields from opposite corners cancel at the centre.

Step 1: Find the field produced by one wire The distance from any corner to the centre O is half the square's diagonal:

$$d = \frac{a}{\sqrt{2}}, \quad B_0 = \frac{\mu_0 I}{2\pi(a/\sqrt{2})} = \frac{\mu_0 I}{\sqrt{2}\pi a}.$$

The fields of the downward currents at opposite corners B and D cancel.

Step 2: Add the fields from the remaining corners The current at A is upward, out of the table. By the right-hand rule its field at O points along OB . The downward current at the opposite corner C also gives a field along OB . Thus these equal fields reinforce:

$$B_{\text{net}} = 2B_0 = \frac{\sqrt{2}\mu_0 I}{\pi a}.$$

Option (B) gives only one wire's magnitude and the opposite direction. Options (A) and (D) have neither the resultant magnitude nor its direction.

Step 3: Conclusion The net field has magnitude $\sqrt{2}\mu_0 I/(\pi a)$ and is directed along OB . Hence, the correct option is (C).

Quick Tip to Solve: Cancel the fields of opposite wires with identical current directions first; the opposite wires with reversed currents reinforce at the centre.

4. The magnetic flux through a loop placed in a magnetic field can be changed by changing: [1 mark]

- (A) area of the loop only
- (B) the value of magnetic field only
- (C) orientation of the loop in the magnetic field only
- (D) any one or more of the factors given in (A), (B) and (C)

Correct Answer: (D) any one or more of the factors given in (A), (B) and (C)

Solution:

Concept:

- Magnetic flux through a plane loop in a uniform magnetic field is $\Phi_B = \vec{B} \cdot \vec{A} = BA \cos \theta$.
- Here B is the magnetic field magnitude, A is the area enclosed by the loop, and θ is the angle between the field and the loop's normal.

Step 1: Identify the quantities controlling flux With the other factors fixed, changing the area changes the amount of field passing through the loop. Similarly, changing the field magnitude changes the flux. Rotating the loop changes θ , and hence changes the projected area $A \cos \theta$ perpendicular to the field.

Step 2: Compare the scope of the options Area, field strength and orientation can each be used to change magnetic flux. Options (A), (B) and (C) incorrectly restrict the possible method with the word *only*. Option (D) correctly allows any one or more of the three factors to be varied. This means they can change the flux; specially compensating changes need not do so.

Step 3: Conclusion Magnetic flux can be changed by changing any one or more of the loop's area, magnetic field or orientation. Hence, the correct option is (D).

Quick Tip to Solve: Write $\Phi_B = BA \cos \theta$ and check each factor; remember that θ is measured from the normal, not the plane.

5. 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 by a transformer, which operates through a changing magnetic flux.
- For power P transmitted at voltage V , a larger voltage permits a smaller current. The resistive line loss is $P_{\text{loss}} = I^2 R$, where R is the line resistance.

Step 1: Check the stated economic advantages In the standard power-system comparison, ac generation is economical, so statement (A) is true. Transformers make conversion between ac voltage levels easy and efficient, validating (B). Stepping up the voltage reduces the current needed for the same transmitted power and therefore reduces heating losses; this explains the transmission advantage in (C).

Step 2: Examine the safety statement These economic advantages do not make ac less dangerous. The danger of an electric current depends on its magnitude, path through the body and duration of contact, as well as its frequency. Mains-frequency ac can be especially hazardous. Thus statement (D) is not a valid general advantage of ac over dc, while (A), (B) and (C) are the intended true statements.

Step 3: Conclusion The statement that ac is less dangerous is *not* true as a general comparison. Hence, the correct option is (D).

Quick Tip to Solve: For this negative-choice question, separate ac's generation and transformer advantages from safety; economical transmission does not imply reduced danger.

6. 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 speed of light in a medium of refractive index n is $v = c/n$, where $c = 3.0 \times 10^8 \text{ m s}^{-1}$.
- For a wave with phase $kx + \omega t$, the wave-number magnitude is $k = \omega/v$. The coefficient of t is the angular frequency ω , not the ordinary frequency.

Step 1: Find the wave speed in glass The refractive index is 1.5, so the electromagnetic wave travels at

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

From the given sine argument, $\omega = 1.5 \times 10^{11} \text{ s}^{-1}$, and α is the wave number.

Step 2: Calculate the spatial coefficient Using the speed in glass gives

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

The plus sign in the phase means propagation along negative x ; it does not make the wave-number magnitude negative. Option (A) incorrectly uses the vacuum speed. The values in (B) and (D) also fail the required relation $v = \omega/\alpha$. The magnetic-field amplitude is irrelevant to this calculation.

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 $\alpha = n\omega/c$; do not insert an extra factor of 2π .

7. Light of which of the following colours will have the maximum energy in a photon associated with it? [1 mark]

- (A) Red light
- (B) Yellow light
- (C) Green light
- (D) Blue light

Correct Answer: (D) Blue light

Solution:

Concept:

- A photon has energy $E = h\nu = hc/\lambda$, where h is Planck's constant, ν is frequency, and λ is wavelength in vacuum.
- Photon energy increases with frequency and decreases with wavelength. It is determined by the colour, not by the light's intensity.

Step 1: Arrange the given colours by wavelength Within the visible spectrum, the listed colours have the order

$$\lambda_{\text{red}} > \lambda_{\text{yellow}} > \lambda_{\text{green}} > \lambda_{\text{blue}}.$$

Thus blue has the shortest wavelength and the highest frequency among these four choices.

Step 2: Compare the energy per photon Since h and c are constants, the relation $E = hc/\lambda$ reverses the wavelength ordering:

$$E_{\text{blue}} > E_{\text{green}} > E_{\text{yellow}} > E_{\text{red}}.$$

Red, yellow and green therefore cannot supply the greatest energy per photon among the options.

Increasing their intensity would increase the photon arrival rate, without increasing the energy of each photon of that colour.

Step 3: Conclusion Blue light has the maximum photon energy among the given colours. Hence, the correct option is (D).

Quick Tip to Solve: For photon-energy comparisons, choose the shortest wavelength among the listed colours; compare individual photons rather than beam intensity.

8. Nuclides with the same number of neutrons are called:

[1 mark]

- (A) Isobars
- (B) Isotones
- (C) Isotopes
- (D) Isomers

Correct Answer: (B) Isotones

Solution:

Concept:

- A nucleus contains Z protons and N neutrons; its mass number is $A = Z + N$.
- Isotones have the same neutron number N , while isotopes have the same atomic number Z and isobars have the same mass number A .

Step 1: Identify the quantity held fixed The question specifies equal numbers of neutrons, so the shared quantity is $N = A - Z$, not necessarily A or Z . For example, ${}^{14}_6\text{C}$ and ${}^{15}_7\text{N}$ each contain eight neutrons although their proton and mass numbers differ.

Step 2: Distinguish the four classifications The definition of isotones in option (B) matches this condition. Isobars in (A) share total nucleon number, and isotopes in (C) share proton number. Nuclear isomers in (D) are different energy states of the same nuclide; this is not the general classification specified merely by equal neutron numbers.

Step 3: Conclusion Nuclides with the same number of neutrons are called **isotones**. Hence, the correct option is (B).

Quick Tip to Solve: When comparing two nuclei, calculate $A - Z$; equal values identify an isotonic pair.

9. 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:

- Nuclear radius follows the empirical relation $R = R_0 A^{1/3}$, where A is the mass number and $R_0 \simeq 1.2$ fm.
- A femtometre is $1 \text{ fm} = 10^{-15} \text{ m}$; the dimensionless mass number enters through its cube root.

Step 1: Find the cube root of the mass number Here $A = 125 = 5^3$, so $A^{1/3} = 5$. The cube-root dependence follows from nuclear volume being proportional to the number of nucleons, since nuclei have approximately constant density.

Step 2: Calculate the radius and compare the options Substitute the mass number into the radius relation:

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

Options (B), (C) and (D), namely 30 fm, 72 fm and 150 fm, do not satisfy this relation. In particular, 150 fm comes from wrongly using $1.2A$ instead of $1.2A^{1/3}$.

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 $125 = 5^3$ first: the radius is five times R_0 , not 125 times R_0 .

10. 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:

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

Step 1: Determine the orbit number from the energy Equate the given energy to the hydrogen energy formula:

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

The negative energy indicates a bound state; it does not make the allowed orbit number negative.

Step 2: Apply angular-momentum quantisation In the second orbit,

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

Option (A) corresponds to $n = 3$, (B) to $n = 4$, and (D) to $n = 1$. None of these orbit numbers gives the stated energy of -3.4 eV .

Step 3: Conclusion The magnitude of the electron's angular momentum is h/π . Hence, the correct option is (C).

Quick Tip to Solve: Use the energy to find n first; -3.4 eV identifies the second orbit, whose angular momentum is $2\hbar$.

11. 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 and allows only a very small leakage current in reverse bias below breakdown.
- At the test voltage of a multimeter, a larger current corresponds to a lower indicated resistance, while a very small current corresponds to a high indicated resistance.

Step 1: Compare the two bias conditions Forward bias lowers the junction barrier and narrows the depletion region, allowing appreciable majority-carrier current. The meter therefore indicates a low resistance. Reverse bias raises the barrier and widens the depletion region, so the current is very small and the indicated resistance is high.

Step 2: Check the possible meter readings The combination in (A) agrees with these two behaviours. High resistance in both directions, as in (B), suggests an open diode; low resistance in both directions, as in (C), suggests a shorted diode. Option (D) reverses the normal forward- and reverse-bias behaviour of a functioning junction.

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 meter connections: a healthy diode should conduct readily in one direction and block in the other.

12. 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 rms voltage is $V_{\text{rms}} = \sqrt{\langle V^2 \rangle}$, where the brackets denote the time average over a complete cycle.
- For a sinusoid, $\langle \sin^2 \omega t \rangle = 1/2$ and $\langle \sin \omega t \rangle = 0$; V_0 is the peak voltage.

Step 1: Calculate the root-mean-square voltage Squaring before averaging makes both half-cycles contribute positively:

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

It is neither $V_0/2$, as in (A), nor V_0/π , as in (B), nor the peak value V_0 , as in (D).

Step 2: Average the signed voltage over a cycle Let $T = 2\pi/\omega$. The equal positive and negative half-cycle areas cancel:

$$V_{\text{av}} = \frac{1}{T} \int_0^T V_0 \sin \omega t \, dt = 0.$$

A nonzero half-cycle average or rectified average must not be used when the question explicitly asks for the average over 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 sinusoidal cycle, cancel the signed areas for the average; square first only when finding the rms value.

13. 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 is $\varepsilon = -d\Phi_{\text{link}}/dt$, where Φ_{link} is the total magnetic flux linkage of the coil.
- For a fixed coil of N identical turns, $\Phi_{\text{link}} = N\Phi$ and $|\varepsilon| = N|d\Phi/dt|$. The rate of change, rather than the amount of flux, determines the emf magnitude.

Step 1: Evaluate the assertion A larger magnetic flux does not by itself imply a larger induced emf. Even a very large flux produces zero emf if it remains constant, whereas a smaller flux changing rapidly can produce a substantial emf. The assertion is therefore false.

Step 2: Evaluate the reason The induced emf is proportional to the time rate of change of flux linkage, not to the flux itself. The proposed direct proportionality to magnetic flux omits the essential time derivative, so the reason is also false.

Step 3: Test the explanation and the answer codes The reason repeats the same incorrect dependence and cannot explain the assertion. Codes (A) and (B) require both statements to be true, while (C) requires a true assertion; each is excluded by Faraday's law. The code for two false statements applies.

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

Quick Tip to Solve: Test any flux-emf claim with a constant magnetic flux: its size can be large, but its zero time derivative gives zero emf.

14. 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, bright fringes occur at $y_n = n\lambda D/d$, while dark fringes occur at $y'_n = (n + 1/2)\lambda D/d$ under the usual small-angle approximation.
- Fringe width is the separation of successive bright fringes or successive dark fringes. Here λ is the wavelength, D the slit-to-screen distance and d the slit separation.

Step 1: Evaluate the assertion Taking the difference of consecutive bright-fringe positions gives $y_{n+1} - y_n = \lambda D/d$. For consecutive dark fringes, the half-integer offset cancels in the difference, giving $y'_{n+1} - y'_n = \lambda D/d$ as well. The two fringe widths are therefore equal, so the assertion is true.

Step 2: Evaluate the reason The stated formula $\beta = \lambda D/d$ is the standard fringe-width expression for this experiment. It applies to both sets of fringes with the same wavelength and geometry, so the reason is true.

Step 3: Determine whether the reason explains the assertion Since both bright and dark fringe widths have the same expression and depend on the same λ , D and d , the formula explains their equality. Thus (B), which denies the explanation, does not apply; (C) and (D) incorrectly declare one or both statements false.

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

Quick Tip to Solve: Distinguish successive fringes of the same kind, separated by β , from an adjacent bright-dark pair, separated by $\beta/2$.

15. 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 is the energy required to separate a nucleus into its nucleons. A larger binding energy per nucleon indicates greater nuclear stability.
- A nuclear reaction releases energy when its products have greater total binding energy than its reactants: $Q = B_{\text{products}} - B_{\text{reactants}} > 0$.

Step 1: Judge the assertion Medium-mass nuclei near the iron region have higher binding energy per nucleon than very heavy or very light nuclei. Fission of a heavy nucleus and fusion of light nuclei move the products toward this more tightly bound region. The resulting increase in total binding energy appears as released energy, so Assertion (A) is true.

Step 2: Judge the reason The general trend stated in Reason (R) is reversed. Beyond the medium-mass peak, binding energy per nucleon generally decreases toward heavier nuclei; in the light-nucleus region it generally increases toward the peak. These are broad trends, with local variations, so Reason (R) is false.

Step 3: Test the explanatory link A false statement cannot explain the true assertion. Options (A) and (B) require both statements to be true, while option (D) requires the assertion to be false; all three are excluded.

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

Quick Tip to Solve: Locate the iron-region peak of the binding-energy-per-nucleon curve: energy-releasing fission and fusion both move nuclei toward that peak.

16. 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:

- Photoelectric emission begins without an observable time lag when light of frequency ν at or above the threshold ν_0 falls on a metal surface.
- In Einstein's photon model, an electron absorbs one photon's energy $h\nu$ in a single interaction: $K_{\max} = h\nu - W_0$, where $W_0 = h\nu_0$ is the work function.

Step 1: Judge the assertion in its context Here the word “spontaneous” means prompt or instantaneous emission upon illumination with light of sufficient frequency. Photoelectrons are observed without the long waiting time predicted by classical energy accumulation. In this intended sense, Assertion (A) is true; the metal does not emit merely because no radiation is applied.

Step 2: Judge the classical prediction In the classical wave picture, radiation energy is spread continuously across the wavefront. At weak intensity an individual electron would receive energy at a small rate and would need a substantial time, potentially hours or days, to collect the work-function energy. Reason (R) correctly states this difficulty of the classical model and is true.

Step 3: Check whether the reason explains prompt emission A prediction of a long delay does not explain the observed absence of delay. Prompt emission is explained by the transfer of a complete photon energy in a single interaction. Thus option (A) wrongly asserts an explanatory link, while options (C) and (D) wrongly reject one or both statements.

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

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

Section B (10 marks)

17(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, electric power is $P = VI = V^2/R$, where V is the applied voltage and R is its resistance.
- Joule's law gives heat produced in time t : $H = I^2Rt = V^2t/R$. As usual for this calculation, the heating-element resistance is treated as constant.

Step 1: Find the resistance from the rated values The rating means the iron consumes 2.2 kW = 2200 W at 220 V. Use these two values together to determine its resistance, rather than combining the rated power with the reduced supply voltage:

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

Step 2: Calculate the heat at the reduced voltage At the actual supply of 110 V, the same resistance draws less power. The heating duration is $t = 10 \times 60 = 600$ s. Therefore,

$$P' = \frac{110^2}{22} = 550 \text{ W},$$
$$H = P't = 550 \times 600 = 3.30 \times 10^5 \text{ J}.$$

Halving the voltage quarters the power because power depends on the square of voltage for a fixed resistance. This also checks the reduction from 2200 W to 550 W.

Step 3: Conclusion (i) The resistance is 22Ω . (ii) The heat produced in 10 minutes at 110 V is $3.30 \times 10^5 \text{ J}$, or 330 kJ.

Quick Tip to Solve: Calculate resistance using both rated values first. With resistance fixed, halving the supply voltage makes the heating power one-quarter.

17(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 gives the resistance of a wire as $R = V/I$, where V is the potential difference and I is the current.
- For a uniform wire, $R = \rho L/A$, where L is its length, A is its cross-sectional area and ρ is the resistivity of the material.

Step 1: Find the wire's resistance The applied potential difference is $V = 2 \text{ V}$, and the resulting current is $I = 4.0 \text{ A}$. Therefore,

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

This is the resistance of this particular wire, which depends on both its material and its dimensions.

Step 2: Convert the area and determine resistivity Because the given unit is an area, square the millimetre-to-metre conversion:

$$A = 1.0 \text{ mm}^2 = 1.0 \times (10^{-3} \text{ m})^2 = 1.0 \times 10^{-6} \text{ m}^2.$$

Rearranging the resistance relation and substituting $L = 1 \text{ m}$,

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

The units check as $\Omega \text{ m}^2/\text{m} = \Omega \text{ m}$; resistivity is a material property at the stated physical conditions.

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

Quick Tip to Solve: Use $\rho = VA/(IL)$ directly after converting the area: $1 \text{ mm}^2 = 10^{-6} \text{ m}^2$, not 10^{-3} m^2 .

18. A plane circular coil is rotated about its vertical diameter with a constant angular speed ω in a uniform horizontal magnetic field. Initially the plane of the coil is parallel to the magnetic field. Draw plots showing the variation of the following physical quantities as the function of ωt , where t represents time elapsed:

- Magnetic flux ϕ linked with the coil, and
- emf induced in the coil.

[2 marks]

Solution:

Concept:

- The flux linkage of an N -turn coil of area A is $\phi = NBA \cos \theta$, where θ is the angle between its chosen positive normal and the magnetic field B .
- Faraday's law gives the signed induced emf, $\varepsilon = -d\phi/dt$. Define the amplitudes $\phi_0 = NBA$ and $\varepsilon_0 = \omega\phi_0$; for one turn put $N = 1$.

Step 1: Set the initial phase and plot the flux Initially the plane of the coil is parallel to the field,

so its normal is perpendicular to the field and $\phi(0) = 0$. Choose the positive normal so that the flux initially increases. With $x = \omega t$, the normal makes angle $\theta = \pi/2 - x$ with the field, giving

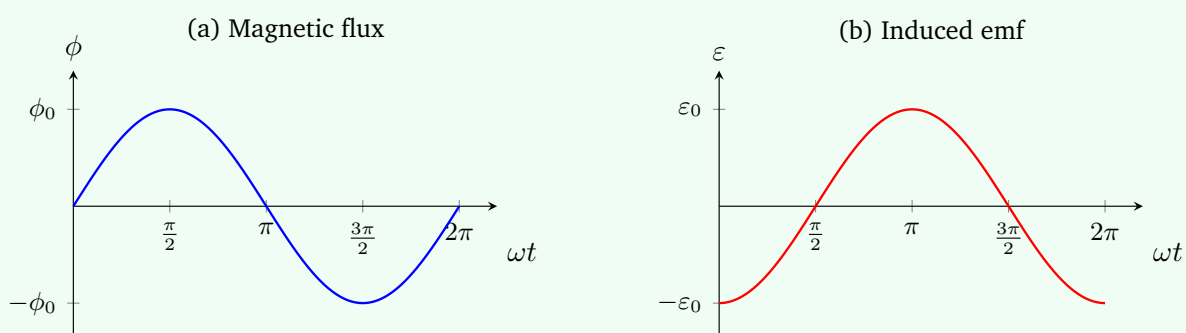
$$\phi = \phi_0 \cos(\pi/2 - x) = \phi_0 \sin x.$$

Thus the flux curve starts from zero, reaches $+\phi_0$ at $x = \pi/2$, returns to zero at π , reaches $-\phi_0$ at $3\pi/2$, and returns to zero at 2π .

Step 2: Differentiate the flux and plot the emf Differentiating with respect to time, rather than only with respect to x , supplies the factor ω :

$$\varepsilon = -\frac{d}{dt}(\phi_0 \sin \omega t) = -\omega \phi_0 \cos \omega t = -\varepsilon_0 \cos x.$$

The emf starts at $-\varepsilon_0$, becomes zero at $\pi/2$, reaches $+\varepsilon_0$ at π , becomes zero at $3\pi/2$, and returns to $-\varepsilon_0$ at 2π . Reversing the reference normal reverses both signed curves without changing the physics.



Flux and induced emf over one rotation; horizontal coordinates are ωt in radians.

Step 3: Conclusion For the stated sign convention, $\phi = \phi_0 \sin \omega t$ and $\varepsilon = -\varepsilon_0 \cos \omega t$. The plots differ in phase by $\pi/2$: emf is zero at flux extrema and has maximum magnitude when flux is zero.

Quick Tip to Solve: First use the initial coil orientation to set the flux phase; then obtain the emf curve as the negative time derivative of that flux curve.

19. A tank is filled with a liquid to a height of 12.5 m. The apparent depth of a needle lying at the bottom of the tank is measured to be 9.0 m. Calculate the speed of light in the liquid. [2 marks]

Solution:

Concept:

- For a liquid viewed from air nearly normally through a plane surface, its refractive index is $\mu = d/d'$, where d is the real depth and d' is the apparent depth.
- The refractive index also satisfies $\mu = c/v$, where $c = 3.0 \times 10^8 \text{ m s}^{-1}$ is the speed of light in vacuum and v is its speed in the liquid; the refractive index of air is taken as unity.

Step 1: Calculate the refractive index The needle is at the bottom, so its real depth equals the liquid height, $d = 12.5 \text{ m}$. Its apparent depth is $d' = 9.0 \text{ m}$. Therefore,

$$\mu = \frac{12.5}{9.0} = 1.3889.$$

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

to come from a shallower point.

Step 2: Relate refractive index to the speed Rearranging $\mu = c/v$ gives the speed of light in the liquid:

$$v = \frac{c}{\mu} = c \frac{d'}{d} = 3.0 \times 10^8 \frac{9.0}{12.5} = 2.16 \times 10^8 \text{ m s}^{-1}.$$

Since the liquid has refractive index greater than one, this speed is correctly smaller than c .

Step 3: Conclusion The speed of light in the liquid is $2.16 \times 10^8 \text{ m s}^{-1}$ (approximately $2.2 \times 10^8 \text{ m s}^{-1}$ to two significant figures).

Quick Tip to Solve: Combine the two refractive-index formulae directly: $v = c \times \text{apparent depth/real depth}$. The smaller depth belongs in the numerator.

20. Two thin lenses of focal length f_1 and f_2 are placed in contact with each other coaxially. Prove that the focal length f of the combination is given by $f = \frac{f_1 f_2}{f_1 + f_2}$. [2 marks]

Solution:

Concept:

- For a thin lens, the Cartesian sign convention gives $1/v - 1/u = 1/f$, where u , v and f are the signed object distance, image distance and focal length.
- For two thin coaxial lenses in contact, the image formed by the first lens acts as the object for the second. Their separation is negligible, so both distances are measured from the same plane.

Step 1: Apply the lens formula to the first lens Let an object be at distance u from the combination. If the first lens alone would form an image at distance v_1 , then

$$\frac{1}{v_1} - \frac{1}{u} = \frac{1}{f_1}.$$

All distances are algebraic, so the equation applies to converging or diverging lenses with their appropriate signs.

Step 2: Apply the lens formula to the second lens The rays leaving the first lens enter the second lens immediately. Its object distance is v_1 , a signed distance that also covers a virtual object. If the final image is at v , then

$$\frac{1}{v} - \frac{1}{v_1} = \frac{1}{f_2}.$$

Adding this equation to the first eliminates the intermediate image distance:

$$\frac{1}{v} - \frac{1}{u} = \frac{1}{f_1} + \frac{1}{f_2}.$$

Step 3: Identify the equivalent focal length A single equivalent thin lens produces the same final image from the same object, so $1/v - 1/u = 1/f$. Comparing gives

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} = \frac{f_1 + f_2}{f_1 f_2}.$$

Taking the reciprocal yields the required form, with the signs of both focal lengths retained.

Step 4: Conclusion The focal length of the combination is $f = \frac{f_1 f_2}{f_1 + f_2}$. If $f_1 + f_2 = 0$, the net power is zero and the equivalent focal length is infinite.

Quick Tip to Solve: Write one lens equation for each lens and add them; the intermediate term $1/v_1$ cancels. Keep focal lengths signed when one lens is diverging.

21. 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 pentavalent. Each ionised arsenic donor supplies one extra conduction electron to silicon, making it an n-type semiconductor with electrons as majority carriers and holes as minority carriers.
- With donor density N_D much greater than the intrinsic carrier concentration n_i , complete donor ionisation gives $n \simeq N_D$. At thermal equilibrium the mass-action law is $np = n_i^2$, where n and p are electron and hole concentrations.

Step 1: Determine the majority carrier concentration Here $N_D = 5 \times 10^{22} \text{ m}^{-3}$ and $n_i = 1.5 \times 10^{16} \text{ m}^{-3}$. Since $N_D \gg n_i$, the usual complete-ionisation approximation gives

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

The silicon atom density is not the free-electron density: most silicon valence electrons are involved in covalent bonds. The donor fraction is $(5 \times 10^{22}) / (5 \times 10^{28}) = 10^{-6}$, or one donor per million silicon atoms.

Step 2: Use the mass-action law for the minority carriers Doping increases the electron concentration and reduces the equilibrium hole concentration. Thus,

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

This is far smaller than the electron concentration, consistent with the n-type classification and the approximation $n \simeq N_D$.

Step 3: Conclusion Majority carriers are electrons, with concentration $n \simeq 5 \times 10^{22} \text{ m}^{-3}$. Minority carriers are holes, with concentration $p \simeq 4.5 \times 10^9 \text{ m}^{-3}$.

Quick Tip to Solve: For a pentavalent dopant, use the donor density for n , then calculate $p = n_i^2/n$; do not use the silicon atom density as a carrier concentration.

Section C (21 marks)

22. Two parallel plate capacitors X and Y are connected in series to a 6 V battery. They have the same plate area and same plate separation but capacitor X has air between its plates, whereas capacitor Y contains a material of dielectric constant 4.

(a) Calculate the capacitances of X and Y , if the equivalent capacitance of the combination of X and Y is $4\text{ }\mu\text{F}$.

(b) Calculate the potential difference across the plates of X and Y .

[3 marks]

Solution:

Concept:

- A parallel-plate capacitor has capacitance $C = K\varepsilon_0 A/d$, where K is the dielectric constant, A is the plate area and d is the separation. Air has $K \simeq 1$.
- Series capacitors carry equal charge magnitude Q , and $1/C_{\text{eq}} = 1/C_X + 1/C_Y$. The voltage across each is $V = Q/C$, so the smaller capacitance has the larger voltage.

Step 1: Relate the two capacitances for part (a) Both capacitors have the same plate area and separation. Their capacitances therefore differ only by the dielectric constant. Let the capacitance of the air-filled capacitor X be C . Then $C_X = C$ and $C_Y = 4C$. Because the capacitors are in series, their equivalent capacitance is

$$C_{\text{eq}} = \frac{C_X C_Y}{C_X + C_Y} = \frac{C(4C)}{C + 4C} = \frac{4C}{5}.$$

Using the given value $C_{\text{eq}} = 4\text{ }\mu\text{F}$,

$$\frac{4C}{5} = 4\text{ }\mu\text{F} \Rightarrow C = 5\text{ }\mu\text{F}.$$

Thus $C_X = 5\text{ }\mu\text{F}$ and $C_Y = 20\text{ }\mu\text{F}$. As expected for a series combination, $4\text{ }\mu\text{F}$ is smaller than either individual capacitance.

Step 2: Calculate the common charge for part (b) The 6 V battery is connected across the entire combination. Hence the charge magnitude on each capacitor is

$$Q = C_{\text{eq}} V = (4\text{ }\mu\text{F})(6\text{ V}) = 24\text{ }\mu\text{C}.$$

The charges have equal magnitudes because the intermediate connecting conductor cannot acquire a net charge in the usual charging arrangement.

Step 3: Find and check the individual voltages Apply $V = Q/C$ separately to the two capacitors:

$$V_X = \frac{24\text{ }\mu\text{C}}{5\text{ }\mu\text{F}} = 4.8\text{ V},$$

$$V_Y = \frac{24\text{ }\mu\text{C}}{20\text{ }\mu\text{F}} = 1.2\text{ V}.$$

Their sum is $4.8 + 1.2 = 6.0\text{ V}$, equal to the battery voltage. Also $V_X/V_Y = 4$, the inverse of the capacitance ratio.

Step 4: Conclusion (a) $C_X = 5\ \mu\text{F}$ and $C_Y = 20\ \mu\text{F}$. (b) The potential differences are $V_X = 4.8\text{ V}$ and $V_Y = 1.2\text{ V}$.

Quick Tip to Solve: First set $C_Y = 4C_X$. For the voltage division, equal series charge gives $V_X : V_Y = 4 : 1$, so split the 6 V supply into five equal parts.

23. 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 $(1\text{ m}, 1\text{ m}, 0)$. [3 marks]

Solution:

Concept:

- The Biot–Savart law gives the magnetic field of a current element as $d\vec{B} = \frac{\mu_0 I d\vec{\ell} \times \vec{r}}{4\pi r^3}$, where $d\vec{\ell}$ points along the current and $\vec{r}$ points from the element to the observation point.
- The cross product fixes the direction: $\hat{i} \times \hat{j} = \hat{k}$. In free space, $\mu_0/(4\pi) = 10^{-7}\text{ T m A}^{-1}$.

Step 1: Represent the short segment as a current element Convert the segment length into SI units: $1\text{ cm} = 10^{-2}\text{ m}$. Since the current is along the positive x -axis, the length vector is $\Delta\vec{\ell} = 10^{-2}\hat{i}\text{ m}$. From its centre at the origin to the given point,

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

The segment length is much smaller than this distance, so its field is calculated using the short-current-element approximation, with $\vec{r}$ measured from its centre.

Step 2: Evaluate the cross product and substitute The component of $\vec{r}$ parallel to the element makes no contribution, while its positive y -component gives a field along positive z :

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

Therefore the magnetic field due to the segment is

$$\begin{aligned} \vec{B} &\simeq \frac{\mu_0 I \Delta\vec{\ell} \times \vec{r}}{4\pi r^3} \\ &= 10^{-7} \frac{10 \times 10^{-2}}{(\sqrt{2})^3} \hat{k}\text{ T} = \frac{10^{-8}}{2\sqrt{2}} \hat{k}\text{ T}. \end{aligned}$$

Equivalently, the angle between the element and $\vec{r}$ is 45° , which supplies the same factor $\sin 45^\circ$ in the scalar form of the law.

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

Quick Tip to Solve: Convert the centimetre segment to metres first; then use the cross product to determine the direction before evaluating the magnitude.

24. A long solenoid of length L and radius r_1 , having N_1 turns is surrounded symmetrically by a coil of radius r_2 ($> r_1$) having N_2 turns ($N_2 \ll N_1$) around its mid-point. Derive an expression for the mutual inductance of solenoid and coil. Is $M_{12} = M_{21}$ valid in this case? [3 marks]

Solution:

Concept:

- Inside a long air-core solenoid, the magnetic field is $B_1 = \mu_0 n_1 I_1$, where $n_1 = N_1/L$ is the number of turns per unit length and I_1 is the solenoid current. The external field is negligible.
- Mutual inductance is the flux linkage of one circuit per unit current in the other: $N_2 \Phi_{21} = M_{21} I_1$. Here the first subscript denotes the circuit receiving the flux, and the second denotes the circuit carrying the current.

Step 1: Find the field produced by the solenoid Let a current I_1 flow through the N_1 -turn solenoid. Since the surrounding coil lies symmetrically around its midpoint, it samples the nearly uniform interior field away from the ends:

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

The magnetic field is directed along the common axis of the solenoid and the coil. We neglect end effects, as appropriate for a long solenoid.

Step 2: Calculate the flux linked with the surrounding coil Although each surrounding turn has area πr_2^2 , appreciable solenoid flux passes only through the common area πr_1^2 . The annular region outside the solenoid contributes negligibly because the external solenoid field is negligible. Thus the flux through one surrounding turn is

$$\Phi_{21} = B_1 \pi r_1^2 = \frac{\mu_0 N_1 I_1 \pi r_1^2}{L}.$$

All N_2 turns link this flux. Dividing the total flux linkage by the solenoid current gives

$$M_{21} = \frac{N_2 \Phi_{21}}{I_1} = \frac{\mu_0 N_1 N_2 \pi r_1^2}{L}.$$

Step 3: Apply reciprocity to the two circuits Yes, $M_{12} = M_{21}$ is valid. Mutual inductance obeys reciprocity for two fixed circuits in air: interchanging the circuit carrying the current and the circuit receiving the flux leaves the mutual inductance unchanged. Unequal turn counts, including $N_2 \ll N_1$, do not alter this property. The field produced by the shorter coil need not be uniform throughout the solenoid for reciprocity to hold; one must compare total flux linkages, rather than individual-turn fluxes.

Step 4: Conclusion For the given arrangement, $M = M_{12} = M_{21} = \frac{\mu_0 N_1 N_2 \pi r_1^2}{L}$, in henries. The effective linked area is the solenoid cross-section, and the equality of the two mutual inductances remains valid.

Quick Tip to Solve: Use the area in which the source solenoid's field exists: the smaller cross-section πr_1^2 , even though the surrounding coil is larger.

25. What is displacement current (i_d)? Considering the case of charging of a capacitor, show that $i_d = \epsilon_0 \frac{d\Phi_E}{dt}$. What is the value of i_d for a conductor across which a constant voltage is applied?

[3 marks]

Solution:

Concept:

- Displacement current is the current associated with a time-varying electric field. In vacuum or air it is $i_d = \epsilon_0 d\Phi_E/dt$, where $\Phi_E = \int \vec{E} \cdot d\vec{A}$ is the electric flux through the chosen surface.
- For a parallel-plate capacitor in air, neglecting edge effects, $E = Q/(\epsilon_0 A)$. Here Q is the magnitude of charge on either plate and A is its area. The charging conduction current is $i = dQ/dt$.

Step 1: Explain the current during capacitor charging When a capacitor is being charged, conduction current flows in the connecting wires and charge accumulates on its plates. Free charges do not cross the insulating gap between the plates, but the electric field in that gap changes with time. Maxwell associated a displacement current with this changing field. It contributes to the magnetic field just as conduction current does and maintains current continuity through the capacitor gap.

Step 2: Relate the changing electric flux to the charging current Consider a flat surface of area A between the plates, perpendicular to their uniform electric field. Choose its normal along $\vec{E}$. Its electric flux is

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

Differentiating with respect to time gives

$$\epsilon_0 \frac{d\Phi_E}{dt} = \frac{dQ}{dt} = i.$$

A surface cutting the charging wire encloses conduction current i , whereas a surface passing through the gap encloses no conduction current. The displacement current in the gap must equal i , so both surfaces give the same magnetic circulation. Hence

$$i_d = \epsilon_0 \frac{d\Phi_E}{dt}.$$

Step 3: Examine a conductor under constant voltage After the initial switching transient has ended, a constant applied voltage produces a time-independent electric field in a fixed conductor. The electric flux is then constant, so $d\Phi_E/dt = 0$. Therefore its displacement current is zero. A steady conduction current may still flow because charge carriers move under this constant electric field; a nonzero conduction current does not require a changing electric field.

Step 4: Conclusion Displacement current is associated with changing electric flux, and for a charging capacitor $i_d = \epsilon_0 \frac{d\Phi_E}{dt} = \frac{dQ}{dt}$. For a conductor under constant voltage in the steady state, $i_d = 0$.

Quick Tip to Solve: For a charging capacitor, first write $\Phi_E = Q/\epsilon_0$ and differentiate. For a steady voltage, check whether the field changes, rather than whether charge flows.

26(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 (nucleons) inside a nucleus; their properties differ from those of the electrostatic force.
- The binding energy B is the energy required to separate a nucleus into its free nucleons. Its rest mass is $M = Zm_p + Nm_n - B/c^2$, where Z, N are the proton and neutron numbers.
- Mass-energy conservation gives the reaction energy $Q = (M_{\text{initial}} - M_{\text{final}})c^2$, with each mass representing the sum of the rest masses on that side.

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

Approximate charge independence: After excluding the electrostatic interaction, the nuclear interaction is approximately the same for proton-proton, neutron-neutron and proton-neutron pairs in corresponding states. Thus nuclear attraction is not determined by whether a nucleon carries electric charge.

Step 2: Relate nuclear mass to binding energy (ii) Even if both the proton count and the neutron count remain unchanged, the nucleons are rearranged into different nuclei in a reaction. These nuclei generally have different total binding energies. Therefore their total rest masses need not be equal: nuclear mass includes the effect of the energy of binding, and is less than the sum of the constituent free-nucleon masses. If B_i and B_f are the total binding energies of the initial and final nuclei, conservation of the nucleon counts gives

$$M_i - M_f = \frac{B_f - B_i}{c^2}, \quad Q = B_f - B_i.$$

Step 3: Explain the direction of energy transfer When the products are more tightly bound in total, $B_f > B_i$, their total rest mass is smaller. The decrease in rest-mass energy appears as kinetic energy of the products and/or radiation. Conversely, a reaction producing a smaller total binding energy requires an input of energy, and the total rest mass increases. It is total mass-energy, rather than rest mass alone, that is conserved.

Step 4: Conclusion Nuclear forces are short-ranged and approximately charge-independent. Conserving the numbers of protons and neutrons does not conserve their total binding energy; the change in binding energy accounts for conversion between rest mass and other forms of energy through $Q = (M_i - M_f)c^2$.

Quick Tip to Solve: Compare total binding energies on the two sides: a larger final binding energy means a smaller final rest mass and a positive energy release.

26(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.

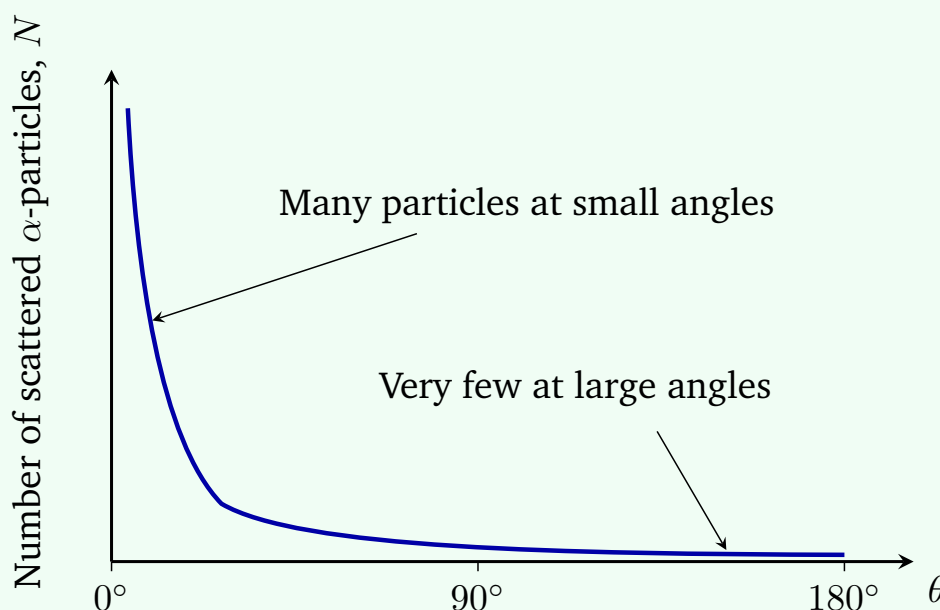
[3 marks]

Solution:

Concept:

- In Rutherford scattering, positively charged α -particles are deflected by electrostatic repulsion from the positive nucleus. Most particles pass with little or no deflection, while very few undergo large-angle scattering.
- For a fixed incident beam and equal small detector solid angles, the Rutherford angular dependence is $N(\theta) \propto 1/\sin^4(\theta/2)$, where θ is the scattering angle and N is the detected count.
- Bohr's quantization condition is $L = n\hbar$, where L is orbital angular momentum, n is a positive integer and $\hbar = h/(2\pi)$. Adjacent permitted values differ by $\hbar$.

Step 1: Draw the angular distribution (i) Put the scattering angle θ on the horizontal axis and the number of scattered α -particles on the vertical axis. The count is very large at small angles, drops rapidly as the angle increases, and is very small but nonzero even at large angles. The sketch shows this qualitative variation; the height of the small-angle peak is not to scale.



Qualitative Rutherford scattering distribution (small-angle peak not to scale).

Step 2: Infer the structure of the atom **First conclusion:** The predominance of particles passing straight through or suffering only small deflections shows that most of the volume of an atom is empty space. There is no extended dense obstacle throughout the atom.

Second conclusion: The very small number of particles deflected through large angles, including backward directions, shows that the positive charge and almost all the atomic mass are concentrated in a very small, dense nucleus. A strong repulsive force is available only during the rare close approaches to this nucleus; a diffuse distribution of positive charge would not explain the large deflections.

Step 3: Compare the angular-momentum spacing with planetary values (ii) A planet has an enormous angular momentum $L = mvr$ on the scale of $\hbar \simeq 1.05 \times 10^{-34}$ J s. If the same quantization condition is applied, its quantum number $n = L/\hbar$ is correspondingly enormous. Hence

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

The separation between adjacent allowed orbital angular momenta, and hence the corresponding change of orbit, is far too small to observe for planets. The allowed values therefore appear continuous on astronomical scales, and classical mechanics describes planetary motion accurately. The absence of observable discrete planetary orbits does not follow from a failure of the stated quantization condition.

Step 4: Conclusion The scattering graph falls steeply from a large small-angle count to a tiny large-angle count. It supports an atom that is mostly empty space with a very small, massive, positively charged nucleus. For planetary motion the quantum number is so large that neighbouring allowed orbits are experimentally indistinguishable.

Quick Tip to Solve: Link the common small deflections to empty space and the rare large deflections to a compact nucleus. For planets, compare the quantum spacing $\hbar$ with the huge classical angular momentum.

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

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

[3 marks]

Solution:

Concept:

- A photon of frequency ν carries energy $E = h\nu$, where h is Planck's constant. One absorbed photon transfers its energy to one electron.
- Einstein's photoelectric equation is $K_{\max} = h\nu - \phi_0$, where ϕ_0 is the work function and $K_{\max}$ is the largest emitted-electron kinetic energy.
- The stopping potential magnitude V_0 satisfies $eV_0 = K_{\max}$. Use $h = 6.63 \times 10^{-34}$ J s, $e = 1.6 \times 10^{-19}$ C, and $1 \text{ eV} = 1.6 \times 10^{-19}$ J.

Step 1: Calculate the incident photon energy (a) Substitute the given frequency $\nu = 6.4 \times 10^{14}$ Hz into the photon-energy relation:

$$E = h\nu = (6.63 \times 10^{-34})(6.4 \times 10^{14}) = 4.2432 \times 10^{-19} \text{ J}.$$

Converting this energy to electronvolts allows direct comparison with the stated work function:

$$E = \frac{4.2432 \times 10^{-19}}{1.6 \times 10^{-19}} \text{ eV} = 2.652 \text{ eV}.$$

Step 2: Subtract the work function (b) The electron must spend $\phi_0 = 1.96$ eV to escape the surface. Since $2.652 \text{ eV} > 1.96 \text{ eV}$, photoemission is possible; the remaining energy gives the maximum kinetic

energy:

$$K_{\max} = 2.652 - 1.96 = 0.692 \text{ eV},$$

$$K_{\max} = 0.692(1.6 \times 10^{-19}) \text{ J} = 1.1072 \times 10^{-19} \text{ J}.$$

Electrons which lose energy before leaving the metal can have smaller kinetic energies, so the subtraction determines the maximum value.

Step 3: Find the retarding potential required to stop all electrons (c) At the stopping potential even the fastest electrons are just prevented from reaching the collector. Their maximum kinetic energy equals the electrical potential-energy barrier:

$$V_0 = \frac{K_{\max}}{e} = \frac{1.1072 \times 10^{-19}}{1.6 \times 10^{-19}} \text{ V} = 0.692 \text{ V}.$$

This is the magnitude of the retarding voltage; the collector is negative relative to the emitting surface.

Step 4: Conclusion (a) The photon energy is $4.24 \times 10^{-19} \text{ J}$, or approximately 2.65 eV. (b) The maximum kinetic energy is $1.11 \times 10^{-19} \text{ J}$, or 0.692 eV. (c) The stopping potential magnitude is 0.692 V, approximately 0.69 V.

Quick Tip to Solve: Convert the photon energy to eV before subtracting the work function. The numerical value of the resulting kinetic energy in eV equals the stopping potential magnitude in volts.

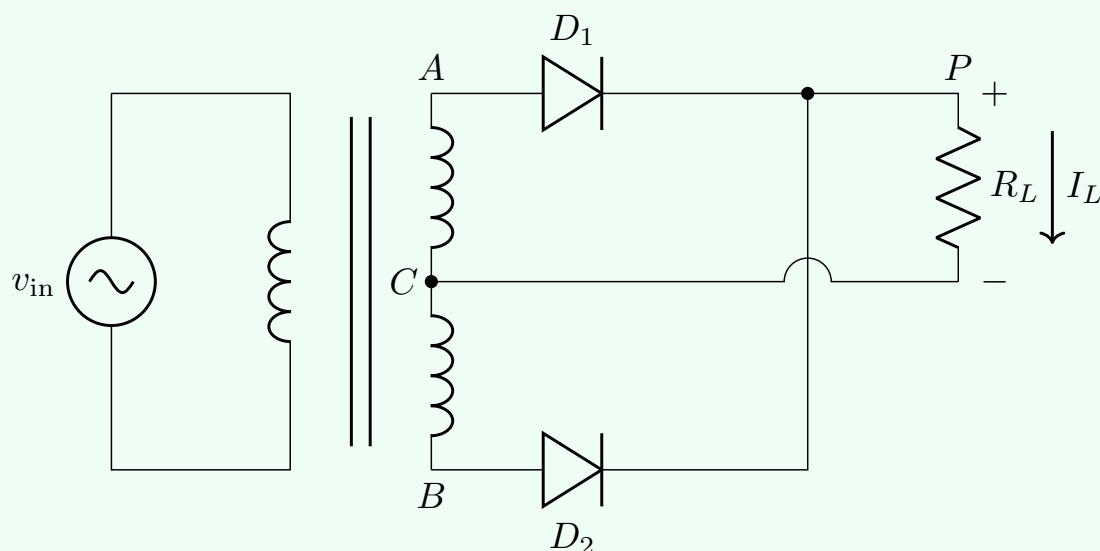
28. Draw a circuit diagram of a full-wave rectifier using p-n junction diodes. Explain its working and show the input-output waveforms. [3 marks]

Solution:

Concept:

- A p-n junction diode conducts appreciably when forward biased and blocks current when reverse biased. Rectification converts an alternating voltage into a unidirectional, pulsating voltage.
- In a centre-tapped full-wave rectifier, the two equal secondary voltages, measured relative to the centre tap C , are opposite in phase: $v_{AC} = V_m \sin \omega t$ and $v_{BC} = -V_m \sin \omega t$.

Step 1: Connect the transformer, diodes and load Connect the anodes of D_1 and D_2 to the secondary ends A and B , respectively. Join their cathodes at P . Connect the load resistance R_L between P and the centre tap C . The primary receives the alternating input. The curved crossover in the return lead shows that it is insulated from the diode connection that it crosses.



Centre-tapped secondary

Centre-tapped full-wave rectifier; the crossover is not a junction.

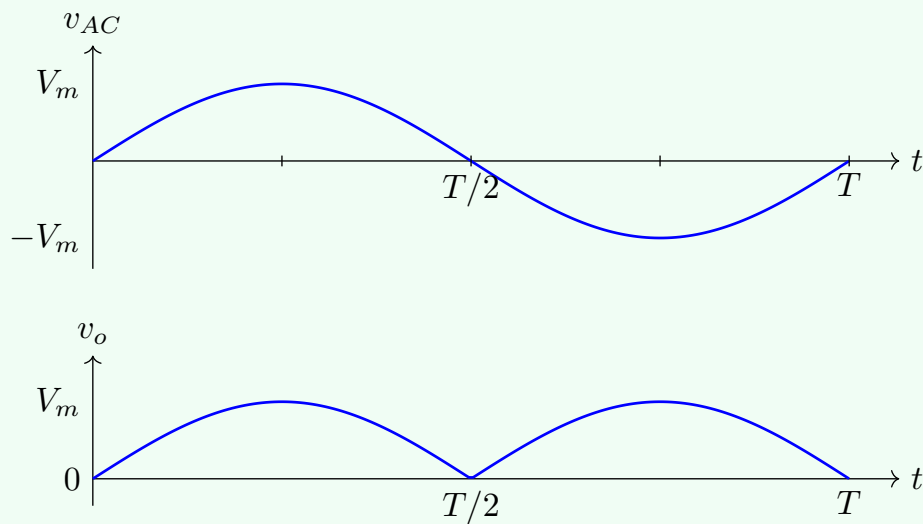
Step 2: Trace current during the positive half-cycle When A is positive relative to C , B is negative. Diode D_1 is forward biased and D_2 is reverse biased. Conventional current flows through A , D_1 , P , R_L and C , returning through the upper half of the secondary winding. Thus the load current flows from P towards C .

Step 3: Trace current during the negative half-cycle When the input reverses, B becomes positive and A negative relative to C . Now D_2 conducts and D_1 blocks. Current flows through B , D_2 , P , R_L and C , returning through the lower half of the secondary winding. Its direction through the load is again from P towards C .

Step 4: Compare the input and output waveforms Neglecting diode voltage drops, the output measured from P to C is

$$v_o = V_m |\sin \omega t|.$$

Both input half-cycles therefore produce positive output pulses. If the input period is T and frequency is f , the output repeats every $T/2$, so its ripple frequency is $2f$. Without a smoothing filter the output is pulsating, rather than constant, direct voltage. The input trace represents one half-secondary voltage; the primary waveform has the same sinusoidal shape.



Sinusoidal input and full-wave rectified output for ideal diodes.

Step 5: Conclusion The two diodes conduct alternately, but the current through R_L has the same direction in both half-cycles. The circuit therefore gives full-wave rectification with a positive pulsating output and ripple frequency $2f$.

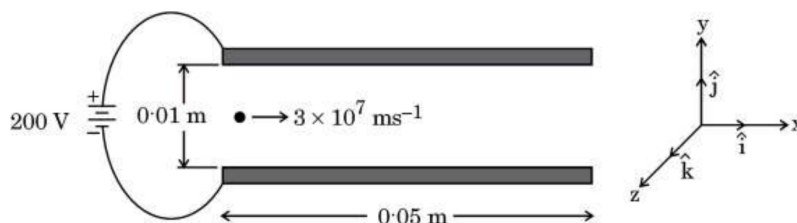
Quick Tip to Solve: Check a full-wave circuit by tracing each conducting diode separately: both routes must cross the load in the same direction, producing two pulses per input cycle.

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 $3 \times 10^7 \text{ ms}^{-1}$ 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:

- For parallel plates, neglecting fringing, the uniform field magnitude is $E = \Delta V/d$, where ΔV is the potential difference and d is their separation.
- The electric field points from the positive plate towards the negative plate, in the direction of decreasing potential.

Step 1: Find the field magnitude The potential difference is 200 V and the separation along the stated z -axis is 0.01 m. Hence

$$E = \frac{200}{0.01} = 2.0 \times 10^4 \text{ V m}^{-1}.$$

The plate length 0.05 m is not the separation and must not be used here. Options (A) and (B) have an incorrect magnitude.

Step 2: Determine the field direction The upper plate is connected to the positive terminal and the lower plate to the negative terminal. Using the stated separation along z and the indicated positive z direction towards the lower plate, the field points along $+\hat{k}$. Option (D) reverses the polarity and therefore gives the wrong direction.

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 voltage by the plate gap, then fix the vector sign from positive to negative plate before checking the options.

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 $\vec{F} = q\vec{E}$, and Newton's second law gives $\vec{a} = q\vec{E}/m$.
- An electron has charge $-e = -1.6 \times 10^{-19} \text{ C}$ and mass $m_e = 9.1 \times 10^{-31} \text{ kg}$; its acceleration is opposite to the electric field.

Step 1: Determine the force direction The field between the plates is $\vec{E} = (200/0.01)\hat{k} = 2 \times 10^4 \hat{k} \text{ V m}^{-1}$. The electron is attracted towards the positive upper plate, so its acceleration is along $-\hat{k}$, not along its initial horizontal velocity. This excludes the positive $\hat{k}$ direction in (B) and both $\hat{i}$ directions in (C) and (D).

Step 2: Calculate the acceleration magnitude Substituting the charge magnitude, field and mass gives

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

The uniform field makes this acceleration constant while the electron remains between the plates. The 10^{13} values in (C) and (D) also have the wrong magnitude.

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: For an electron, compute eE/m_e as a positive magnitude and then reverse the field direction to obtain the acceleration vector.

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:

- Motions perpendicular to each other can be treated independently. The field acts normal to the plates, so there is no horizontal acceleration.
- The time to traverse horizontal length L at constant horizontal velocity v_x is $t = L/v_x$, provided the electron does not first hit a plate.

Step 1: Use the horizontal motion The initial horizontal speed remains $v_x = 3 \times 10^7 \text{ m s}^{-1}$. The electron traverses the plate length $L = 0.05 \text{ m}$, not the vertical plate gap 0.01 m . Therefore

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

Step 2: Check that the electron can reach the far edge The transverse acceleration has magnitude $a = e(200/0.01)/m_e \simeq 3.52 \times 10^{15} \text{ m s}^{-2}$. Starting midway with zero transverse velocity, its deflection in the calculated time is $\frac{1}{2}at^2 \simeq 4.9 \text{ mm}$, slightly less than the 5 mm distance to the upper plate. It therefore leaves through the far end. Option (B) is ten times too large; (A) and (D) also fail the horizontal distance-time relation.

Step 3: Conclusion The electron remains in the region for $1.67 \times 10^{-9} \text{ s}$. Hence, the correct option is (C).

Quick Tip to Solve: Use the plate length divided by the horizontal speed for transit time, then check that the transverse deflection is smaller than half the gap.

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 electron's transverse acceleration magnitude is $a = eE/m_e$, where $E = \Delta V/d$; the force is towards the positive plate.
- With zero initial transverse velocity, the displacement magnitude is $s = \frac{1}{2}at^2$. The time in the field follows from the independent horizontal motion: $t = L/v_x$.

Step 1: Find the transit time and transverse acceleration The horizontal speed is unchanged because the field is perpendicular to it. Thus

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

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

Step 2: Calculate the transverse displacement The electron enters horizontally, so its initial transverse velocity is zero. Using the unrounded transit time,

$$s = \frac{1}{2}(3.52 \times 10^{15}) \left(\frac{0.05}{3 \times 10^7} \right)^2 \simeq 4.9 \times 10^{-3} \text{ m} = 4.9 \text{ mm}.$$

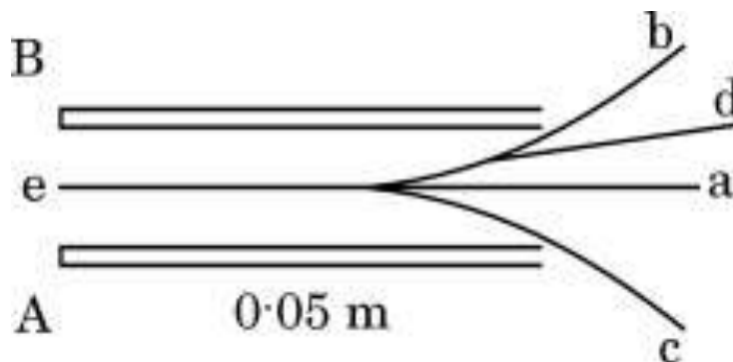
This is slightly smaller than half the gap, 5 mm, so the electron reaches the exit without striking the positive plate. Options (A), (C) and (D) do not match the displacement; in particular, 10 mm is the full plate separation, not the electron's deflection.

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

Quick Tip to Solve: Find the travel time from horizontal motion first, then use half the transverse acceleration times that time squared; convert metres to millimetres last.

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:

- A particle moving with uniform horizontal velocity and constant perpendicular acceleration follows a parabolic path while inside the uniform electric field.
- An electron is negatively charged, so the electric force deflects it towards the positive plate, opposite to the direction of the field.

Step 1: Determine which plate attracts the electron The shared circuit diagram connects the upper plate to the positive terminal. Hence the electron bends upwards towards the upper plate, labelled *B* in the path sketch. The straight horizontal path *a* would require zero transverse force; the downward-curving path *c* would describe the opposite sign of transverse acceleration.

Step 2: Identify the curved trajectory Let u denote displacement towards the upper plate and let x be the distance travelled horizontally from entry. Since $x = v_x t$ and $u = \frac{1}{2} a t^2$, elimination of time gives

$$u = \frac{a}{2v_x^2} x^2.$$

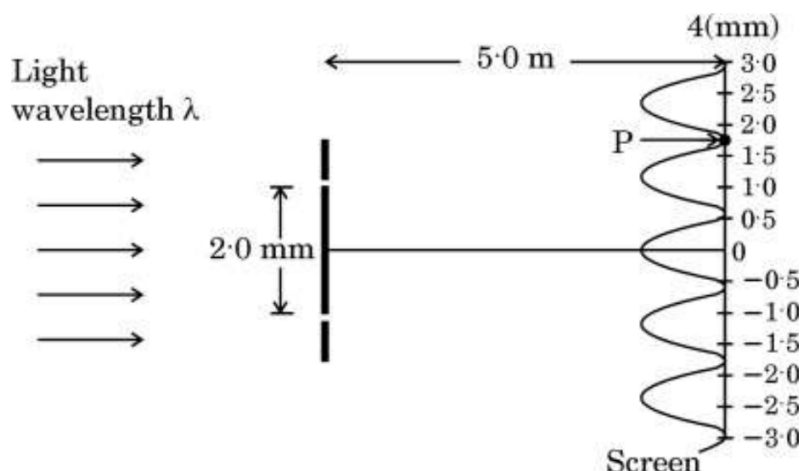
Thus the slope increases continuously from zero: the trajectory must curve upwards. The upward straight line *d* would have constant slope and cannot describe the motion within the uniform field. The drawn upward-curving trajectory is labelled *b*.

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

Quick Tip to Solve: Choose the curve by two checks: negative charge bends towards the positive plate, and constant transverse acceleration produces a parabola inside the plates.

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 light intensity when coherent waves superpose; their relative phase determines whether a bright or dark fringe forms.
- Polarisation, rather than interference alone, distinguishes transverse waves from longitudinal waves.

Step 1: Relate the fringes to superposition At points where the two light waves arrive in phase, their electric-field amplitudes reinforce and produce a bright fringe. Where they arrive in opposite phase, they cancel and produce a dark fringe. This alternating pattern follows the superposition principle for waves.

Step 2: Check the competing interpretations A particle-only description does not explain the alternating constructive and destructive interference in this experiment, so option (B) is unsuitable. Interference can also occur for longitudinal waves, such as sound; hence it does not by itself establish that light is transverse. This excludes (C) and the additional transverse-nature claim in (D).

Step 3: Conclusion Young's double-slit interference experiment demonstrates the wave nature of light. Hence, the correct option is (A).

Quick Tip to Solve: Associate interference with wave nature; use polarisation when the question asks for evidence of transverse nature.

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 experiment, the fringe width is $\beta = \lambda D/d$, where λ is the wavelength, D is the slit-to-screen distance, and d is the slit separation.
- Fringe width is the distance between consecutive bright fringes or consecutive dark fringes, not between a bright fringe and its neighbouring dark fringe.

Step 1: Read the fringe spacing from the diagram The central bright fringe is at $y = 0$, and the next bright fringe is at about $y = 1.2$ mm. Equivalently, the successive minima at 0.6 mm and 1.8 mm are separated by the same distance. Thus $\beta = 1.2 \times 10^{-3}$ m. The supplied geometry gives $d = 2.0 \times 10^{-3}$ m and $D = 5.0$ m.

Step 2: Calculate the wavelength Rearranging the fringe-width relation and using SI units gives

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

Since $1 \text{ nm} = 10^{-9} \text{ m}$, this value is 480 nm. The other proposed wavelengths, 720, 590 and 364 nm, would give fringe widths 1.8, 1.475 and 0.91 mm, respectively, which do not match the diagram.

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

Quick Tip to Solve: Read the spacing between two successive maxima first, then convert both millimetre distances to metres before using $\lambda = \beta d/D$.

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:

- The fringe width β is the distance on the screen between two consecutive maxima or between two consecutive minima of the intensity pattern.
- A bright fringe and its adjacent dark fringe are separated by $\beta/2$, whereas consecutive bright fringes have spacing β .

Step 1: Identify repeated points on the intensity curve The curve has a central maximum at $y = 0$ and its next maximum at approximately $y = 1.2$ mm. Its first two positive-side minima occur at approximately $y = 0.6$ mm and $y = 1.8$ mm. Either pair of consecutive extrema of the same kind measures one full fringe width.

Step 2: Subtract the screen coordinates Using the two consecutive minima gives

$$\beta = (1.8 - 0.6) \text{ mm} = 1.2 \text{ mm}.$$

This agrees with the maximum-to-maximum spacing $(1.2 - 0)$ mm. The distances 0.2, 4.2 and 6.8 mm in options (B), (C) and (D) do not correspond to the spacing of adjacent maxima or adjacent minima in the given pattern.

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

Quick Tip to Solve: Choose two neighbouring peaks or two neighbouring troughs; peak-to-trough spacing would give only half the fringe width.

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) 8.1×10^{-7} m

(B) 7.2×10^{-7} m

(C) 6.5×10^{-7} m

(D) 6.0×10^{-7} m

Correct Answer: (B) 7.2×10^{-7} m

Solution:

Concept:

- For a point at transverse distance y from the centre of a distant screen, the magnitude of the path difference is $\Delta = dy/D$, where d is the slit separation and D is the screen distance.
- Destructive interference occurs at $\Delta = (2n - 1)\lambda/2$, where $n = 1, 2, \dots$ counts the dark fringes from the centre.

Step 1: Locate the specified minimum Point P is the second minimum above the central bright fringe. The diagram places it at about $y_P = 1.8$ mm, between the 1.5 mm and 2.0 mm ticks. The given slit separation is $d = 2.0$ mm, and the screen distance is $D = 5.0$ m.

Step 2: Find and check the path difference Converting both millimetre lengths to metres gives

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

As a check, the measured fringe width gives $\lambda = 4.8 \times 10^{-7}$ m, so the second minimum has $\Delta_P = 3\lambda/2$, which is the same value. The other listed path differences 8.1, 6.5 and 6.0, all in units of 10^{-7} m, do not satisfy this second-minimum condition.

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

Quick Tip to Solve: Count dark fringes from the central bright fringe: the second dark fringe has path difference $3\lambda/2$, not $\lambda/2$.

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 uniform liquid of refractive index μ , light has speed $v = c/\mu$. Its frequency f remains unchanged, so its wavelength becomes $\lambda' = \lambda/\mu$.
- Young's fringe-width relation is $\beta = \lambda D/d$, with D the screen distance and d the slit separation.

Step 1: Apply the change of wavelength Performing the experiment in the liquid fills the propagation region with the same medium. The source frequency and apparatus dimensions remain fixed, while the wavelength decreases because $\mu > 1$. Both coherent beams experience this common change.

Step 2: Compare the fringe widths The new fringe width is

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

Consequently, neighbouring bright fringes and neighbouring dark fringes move closer together. The uniform medium does not destroy coherence, so the pattern need not disappear or become blurred, excluding (A) and (B). Widening, option (C), would require an increase of wavelength, whereas the wavelength here decreases.

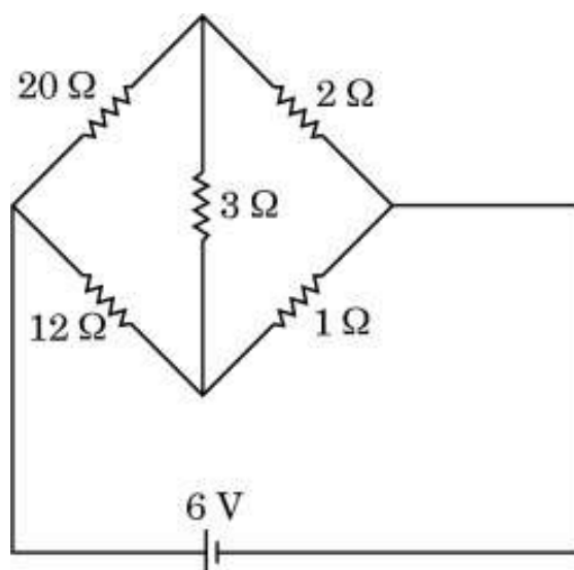
Step 3: Conclusion The fringe pattern is compressed, with fringe width reduced by the factor μ . Hence, the correct option is (D).

Quick Tip to Solve: For the same double-slit apparatus immersed in a uniform liquid, divide both wavelength and fringe width by the refractive index.

Section E (15 marks)

- 31(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:

- In a balanced Wheatstone bridge, the two junctions joined by the galvanometer are at the same potential, so no current passes through the galvanometer.
- Ohm's law gives the potential drop across a resistor as $V = IR$. Kirchhoff's junction rule states that the algebraic sum of currents leaving a junction is zero.
- Label the left, upper, right and lower vertices A, B, C, D , respectively. Let $AB = P$, $BC = Q$, $AD = R$, $DC = S$, with the source across AC and the bridge branch across BD .

Step 1: (i) Apply the zero-current condition At balance, $I_g = 0$ through BD , hence $V_B = V_D$. Let I_1 flow through the upper path ABC and I_2 through the lower path ADC . Since no current leaves either path through the bridge branch, the same current flows through both resistors of each path. Equating potential drops from A to the equipotential junctions gives

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

Equating potential drops from those junctions to C similarly gives

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

Step 2: Eliminate the two branch currents Divide the two equalities to eliminate I_1 and I_2 :

$$\frac{I_1 P}{I_1 Q} = \frac{I_2 R}{I_2 S} \implies \frac{P}{Q} = \frac{R}{S}.$$

Conversely, when these ratios are equal, both series paths divide the applied voltage in the same proportion. Thus $V_B = V_D$, confirming the balance condition.

Step 3: (ii) Set the potentials for the given circuit Here $P = 20\ \Omega$, $Q = 2\ \Omega$, $R = 12\ \Omega$ and $S = 1\ \Omega$.

Since $20/2 = 10$ but $12/1 = 12$, the bridge is unbalanced; the current through 3Ω cannot be set to zero. The longer plate of the 6 V cell is connected to the left vertex. Choose $V_A = 6\text{ V}$, $V_C = 0$, and let the junction potentials be V_B and V_D .

Step 4: Apply Kirchhoff's rule at both junctions Express each outward current as the potential difference divided by its branch resistance. At B and D , respectively,

$$\begin{aligned}\frac{V_B - 6}{20} + \frac{V_B}{2} + \frac{V_B - V_D}{3} &= 0, \\ \frac{V_D - 6}{12} + \frac{V_D}{1} + \frac{V_D - V_B}{3} &= 0.\end{aligned}$$

With potentials in volts and resistances in ohms, these equations give currents in amperes. Multiplying the first equation by 60 and the second by 12 yields

$$\begin{aligned}53V_B - 20V_D &= 18, \\ -4V_B + 17V_D &= 6.\end{aligned}$$

Step 5: Solve for the bridge-branch current Multiply the first reduced equation by 17 and the second by 20, then add. Thus $821V_B = 426$; substituting back gives

$$V_B = \frac{426}{821}\text{ V}, \quad V_D = \frac{390}{821}\text{ V}.$$

Taking the current in BD as positive from the upper vertex to the lower vertex,

$$I_{BD} = \frac{V_B - V_D}{3} = \frac{426 - 390}{821 \times 3}\text{ A} = \frac{12}{821}\text{ A}.$$

Its positive sign confirms that the upper junction is at the higher potential.

Step 6: Conclusion (i) The Wheatstone bridge is balanced when $P/Q = R/S$, equivalently $PS = QR$, and its bridge current is zero. (ii) For the given unbalanced circuit, the current through 3Ω is $1.46 \times 10^{-2}\text{ A}$, approximately 14.6 mA , from the upper vertex towards the lower vertex.

Quick Tip to Solve: First compare the two arm ratios. If they differ, retain the bridge resistor and use two junction-potential equations; the sign of $(V_B - V_D)/3$ gives the current direction.

- 31(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:**

- If n is the number of free electrons per unit volume, e the magnitude of electronic charge, A the cross-sectional area and v_d the drift speed, the conventional-current magnitude is $I = neAv_d$.
- For an electron of mass m and mean relaxation time τ , the drift speed is $v_d = eE\tau/m$. Conductivity σ is defined by $\vec{J} = \sigma\vec{E}$, where $\vec{J}$ is current density.
- In the linear approximation, $\rho_T = \rho_{T_0}[1 + \alpha_{T_0}(T - T_0)]$. Here α_{T_0} is the fractional increase in resistivity per degree relative to its value at reference temperature T_0 .

Step 1: (i) Relate the transported charge to drift speed In a time interval Δt , electrons drift a distance $v_d\Delta t$. All electrons in the volume $Av_d\Delta t$ cross a chosen section of the conductor. Their number is $nAv_d\Delta t$, so the magnitude of charge crossing that section is

$$\Delta Q = neAv_d\Delta t.$$

Therefore, the current and current density have magnitudes

$$I = \frac{\Delta Q}{\Delta t} = neAv_d, \quad J = \frac{I}{A} = nev_d.$$

Electron drift is opposite to the electric field, whereas conventional current is along it because electrons have negative charge.

Step 2: Substitute the drift-speed expression Using the given result $v_d = eE\tau/m$,

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

Comparing this expression with $J = \sigma E$ identifies the coefficient of E . Equivalently, if the potential difference along the cylinder is V , then $E = V/l$, and

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

Thus $\rho = RA/l = m/(ne^2\tau)$, whose reciprocal is the conductivity. The material property is independent of the cylinder's length and area.

Step 3: (ii) Choose the measured lower temperature as reference Take $T_0 = 20^\circ\text{C}$, $R_{20} = 1.05\ \Omega$, and $R_{100} = 1.38\ \Omega$. Neglecting the small thermal change in dimensions, $R = \rho l/A$ implies that resistance and resistivity have the same fractional change. Hence

$$R_{100} = R_{20}[1 + \alpha_{20}(100 - 20)].$$

Rearranging before substitution gives

$$\begin{aligned}\alpha_{20} &= \frac{R_{100} - R_{20}}{R_{20}(100 - 20)} \\ &= \frac{1.38 - 1.05}{1.05 \times 80} \text{ K}^{-1} \\ &= 3.93 \times 10^{-3} \text{ K}^{-1}.\end{aligned}$$

A temperature interval has the same numerical value in kelvin and degrees Celsius. The positive coefficient agrees with the increase in the resistance of this metal on heating.

Step 4: State the reference-temperature convention explicitly The coefficient is normalised to the resistivity at the chosen reference temperature. If it is instead defined relative to 0°C by $R_T = R_0(1 + \alpha_0 T)$, the same data give

$$\alpha_0 = \frac{R_{100} - R_{20}}{100R_{20} - 20R_{100}} = \frac{0.33}{105 - 27.6} \text{ K}^{-1} = 4.26 \times 10^{-3} \text{ K}^{-1}.$$

These two coefficients use different reference resistivities and describe the same linear resistance-versus-temperature relation. With the supplied lower temperature as reference, the coefficient is α_{20} .

Step 5: Conclusion (i) The conductivity is $\sigma = ne^2\tau/m$. (ii) Taking 20°C as the reference, the temperature coefficient of resistivity is $\alpha_{20} = 3.93 \times 10^{-3} \text{ K}^{-1}$. If quoted relative to 0°C , its value is $\alpha_0 = 4.26 \times 10^{-3} \text{ K}^{-1}$.

Quick Tip to Solve: Use $J = nev_d$ to obtain conductivity directly. For the temperature coefficient, divide the change in resistance by the reference resistance and the temperature interval, and name that reference temperature.

32(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:

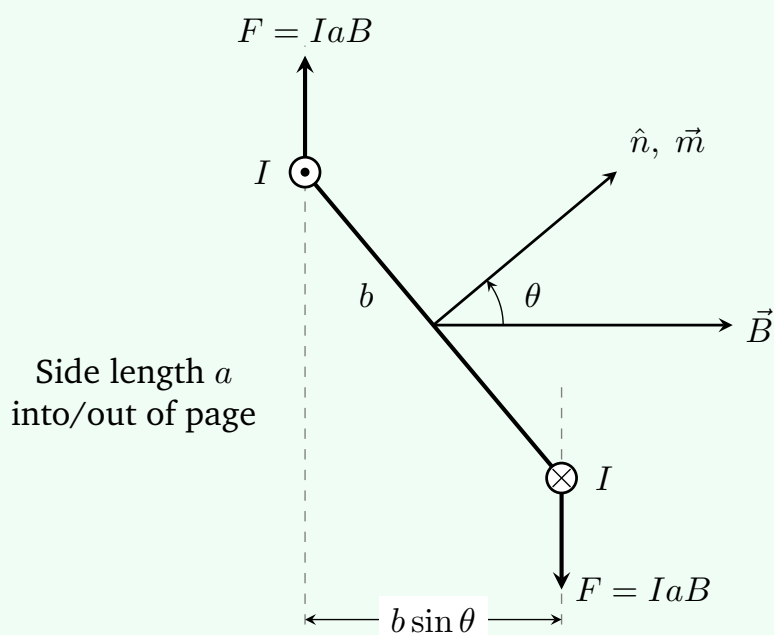
- A straight current-carrying side experiences magnetic force $\vec{F} = I\vec{l} \times \vec{B}$, where $\vec{l}$ points along the current and has magnitude equal to the side length.
- Equal and opposite parallel forces form a couple: its torque magnitude is one force multiplied by the perpendicular distance between their lines of action.
- A plane loop has magnetic moment $\vec{m} = I\vec{A}$; for N identical turns, $\vec{m} = NI\vec{A}$. The area normal is

fixed by the right-hand rule for the current.

Step 1: (i) Identify the pair of forces producing rotation Consider a uniform field and choose the two opposite sides of length a perpendicular to $\vec{B}$. Let $\hat{n}$ be the area normal, making angle θ with the field. Each of these sides experiences a force of magnitude

$$F = Iab.$$

The currents in these sides are opposite, so their forces are equal and opposite. The figure views the loop along these sides: a dot denotes current towards the observer and a cross denotes current away from the observer. The line joining the sides represents the side of length b . Forces on the other two sides are also equal and opposite; they are collinear through their midpoints and give no resultant torque. Thus the net force on the complete loop is zero, while the shown pair forms a couple.



View along the sides of length a : the two forces form a couple with arm $b \sin \theta$.

Step 2: (i) Obtain the magnitude and vector direction of torque The plane of the loop is perpendicular to $\hat{n}$. Therefore the perpendicular separation of the two force lines shown in the diagram is $b \sin \theta$. Equivalently, each force has a moment arm $(b/2) \sin \theta$ about the centre, and their moments add:

$$\begin{aligned} \tau &= 2F \left(\frac{b}{2} \sin \theta \right) \\ &= IabB \sin \theta = IAB \sin \theta, \quad A = ab. \end{aligned}$$

With $m = IA$, this is $\tau = mB \sin \theta$. The torque rotates the normal towards the field; its right-hand-rule direction is perpendicular to both $\vec{m}$ and $\vec{B}$, along $\vec{m} \times \vec{B}$. In the illustrated orientation it is into the page. Hence the magnitude and direction together give

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

Step 3: (ii)(I) Calculate the magnetic dipole moment Convert the radius to metres before calculating

the area of one turn:

$$r = \frac{10}{\sqrt{\pi}} \text{ cm} = \frac{0.10}{\sqrt{\pi}} \text{ m},$$
$$A = \pi r^2 = \pi \frac{(0.10)^2}{\pi} = 1.0 \times 10^{-2} \text{ m}^2,$$
$$m = NIA = 100(5.0)(1.0 \times 10^{-2}) = 5.0 \text{ A m}^2.$$

The magnetic moment points along the coil's normal, with its sense determined by the current.

Step 4: (ii)(II) Balance the magnetic torque The given angle is between the magnetic field and the normal, so it is directly the angle used in the sine factor:

$$\begin{aligned}\tau &= mB \sin 30^\circ \\ &= (5.0)(2.0) \left(\frac{1}{2}\right) \\ &= 5.0 \text{ N m}.\end{aligned}$$

To prevent turning, the applied torque must make the total torque zero. Thus

$$\vec{\tau}_{\text{counter}} = -\vec{\tau};$$

its magnitude equals the magnetic torque and its direction is opposite.

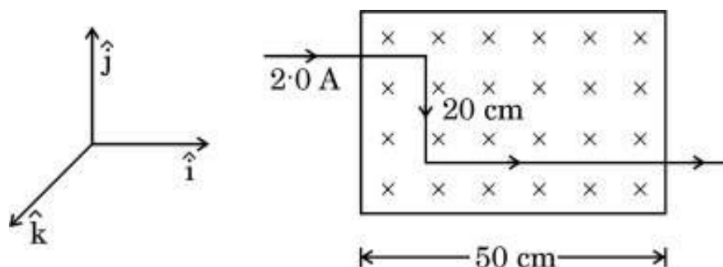
Step 5: Conclusion The rectangular loop obeys $\vec{\tau} = \vec{m} \times \vec{B}$, with $\vec{m} = I\vec{A}$. For the given coil, the magnetic moment has magnitude 5.0 A m^2 , and the required counter torque has magnitude 5.0 N m , opposite to the magnetic torque.

Quick Tip to Solve: Square the radius only after converting centimetres to metres; here the π cancels. Use $\sin 30^\circ$ because the angle is given with the normal, and include all 100 turns.

32(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 carrier of charge q with drift velocity $\vec{v}_d$ experiences magnetic force $q\vec{v}_d \times \vec{B}$. Random thermal velocities average to zero.
- The current density is $\vec{J} = nq\vec{v}_d$, where n is the number of mobile charge carriers per unit volume. For a uniform wire of cross-sectional area A , $\vec{J} = (I/A)\hat{l}$, where $\hat{l}$ points along conventional current.
- In a uniform magnetic field, the force on a bent wire is $\vec{F} = I \int d\vec{l} \times \vec{B} = I(\vec{r}_{\text{out}} - \vec{r}_{\text{in}}) \times \vec{B}$. Only the part of the wire inside the field region contributes.

Step 1: (i) Sum the magnetic forces on the moving charges Consider the straight conductor of length L , cross-sectional area A , and uniform carrier density n . Its volume is AL , so the total number of mobile charge carriers is nAL . In a uniform magnetic field, summing the force on each carrier gives the magnetic force transmitted to the conductor:

$$\begin{aligned}\vec{F} &= (nAL)q\vec{v}_d \times \vec{B} \\ &= AL(nq\vec{v}_d) \times \vec{B} = AL\vec{J} \times \vec{B}.\end{aligned}$$

For a metal, $q = -e$ and the electron drift is opposite to conventional current; their product $q\vec{v}_d$ points along the current. Thus the current direction used below is unchanged by the negative sign of the electron charge.

Step 2: (i) Express the result in terms of the current Substitute $\vec{J} = (I/A)\hat{l}$ and define $\vec{L} = L\hat{l}$, a length vector along the conventional current:

$$\begin{aligned}\vec{F} &= AL\frac{I}{A}\hat{l} \times \vec{B} \\ &= I\vec{L} \times \vec{B}, \\ F &= ILB \sin \phi.\end{aligned}$$

Here ϕ is the angle between the current and the magnetic field. The force is perpendicular to both, as given by the cross product or Fleming's left-hand rule. The cross-sectional area cancels because the current already accounts for the number of charges passing per unit time.

Step 3: (ii) Identify the lengths inside the field From the printed figure, the current enters the field towards $+\hat{i}$, moves down through 20 cm along $-\hat{j}$, then continues towards $+\hat{i}$. The two horizontal

portions inside the field together span the field region's width of 50 cm. If their lengths are l_1 and l_2 , then $l_1 + l_2 = 0.50$ m. Hence the directed sum of the in-field segments is

$$\vec{L}_{\text{eff}} = (l_1 + l_2)\hat{i} - 0.20\hat{j} = (0.50\hat{i} - 0.20\hat{j}) \text{ m.}$$

This is the displacement from entry to exit, rather than the total wire length. The field is zero outside the rectangular region, so the external portions exert no additional magnetic force.

Step 4: (ii) Add the force components and find their resultant Substitute $I = 2.0$ A and $\vec{B} = -(0.50 \text{ T})\hat{k}$. Using $\hat{i} \times \hat{k} = -\hat{j}$ and $\hat{j} \times \hat{k} = \hat{i}$,

$$\begin{aligned}\vec{F} &= I\vec{L}_{\text{eff}} \times \vec{B} \\ &= 2.0(0.50\hat{i} - 0.20\hat{j}) \times (-0.50\hat{k}) \text{ N} \\ &= (0.20\hat{i} + 0.50\hat{j}) \text{ N}, \\ F &= \sqrt{(0.20)^2 + (0.50)^2} \text{ N} \\ &= \sqrt{0.29} \text{ N} \simeq 0.54 \text{ N}.\end{aligned}$$

The downward portion produces the rightward 0.20 N component, while the two horizontal portions together produce the upward 0.50 N component. These components are perpendicular, so their magnitudes must be combined by the Pythagorean theorem.

Step 5: Conclusion For a straight conductor, $\vec{F} = I\vec{L} \times \vec{B}$, with magnitude $ILB \sin \phi$. For the bent wire, $\vec{F} = (0.20\hat{i} + 0.50\hat{j}) \text{ N}$, so the required net force magnitude is 0.54 N.

Quick Tip to Solve: In a uniform field, replace the bent in-field path by its entry-to-exit displacement. Here use $0.50\hat{i} - 0.20\hat{j}$ metres; adding the three segment lengths would lose the force directions.

33(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, different points of the illuminated slit act as coherent secondary sources. Their waves superpose at each point of the screen.
- For a slit of width a , the path difference between rays from its extreme edges in a direction θ is $a \sin \theta$. Here λ is the wavelength and D is the slit-to-screen distance.
- In the usual far-field diffraction arrangement, the intensity is $I = I_0(\sin \beta / \beta)^2$, where $\beta = \pi a \sin \theta / \lambda$ and I_0 is the central intensity. For small angles, the screen coordinate is $y \simeq D\theta$.

Step 1: (i)(I) Explain the central maximum At the point on the screen directly opposite the centre of the slit, $\theta = 0$. All parts of the slit send waves with the same phase to this point, so their amplitudes add constructively. This produces the brightest, central maximum. The apparent 0/0 in the intensity expression is evaluated by $\sin \beta / \beta \rightarrow 1$ as $\beta \rightarrow 0$, giving $I = I_0$.

Step 2: (i)(I) Obtain the minima by pairwise cancellation For a direction satisfying $a \sin \theta = \lambda$, divide the slit into two equal halves. Each point in one half has a corresponding point in the other half separated by $a/2$. The path difference of the waves from such a pair is

$$\frac{a}{2} \sin \theta = \frac{\lambda}{2}.$$

The paired waves have equal amplitudes and opposite phases, so every pair cancels and the first minimum occurs. More generally, when $a \sin \theta = n\lambda$, divide the slit into $2n$ equal strips and pair neighbouring strips. Corresponding points again have path difference $\lambda/2$, so cancellation is complete:

$$a \sin \theta_n = \pm n\lambda, \quad n = 1, 2, 3, \dots$$

The two first minima lie at $y \simeq \pm \lambda D/a$; hence the central maximum has width $2\lambda D/a$.

Step 3: (i)(I) Explain the secondary maxima Between two successive minima, cancellation is incomplete. The resultant amplitude rises from zero, reaches a local maximum, and then falls to zero at the next minimum, producing 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, not exact equalities. For example, near $a \sin \theta = 3\lambda/2$, dividing the slit into three equal strips lets two strips cancel in pairs, leaving a much smaller resultant from the remaining strip. This explains why a secondary maximum is weaker than the central one.

Step 4: (i)(II) Explain why successive maxima become weaker At higher orders, more portions of the slit mutually cancel, and the effective uncanceled contribution becomes smaller. The intensity expression makes the decrease quantitative: near the n -th secondary maximum, $\beta \simeq (n + 1/2)\pi$ and $\sin^2 \beta \simeq 1$, so

$$\frac{I_n}{I_0} \simeq \frac{1}{\pi^2(n + 1/2)^2}.$$

Thus the intensities decrease rapidly with increasing order n . The decrease is caused by the progressive cancellation of secondary wavelets across the slit.

Step 5: (ii) State two differences between the patterns **1. Width of bright bands:** For ideal double-slit interference, successive bright fringes have equal widths $\lambda D/d$, where d is the slit separation. In single-slit diffraction, the central bright band has width $2\lambda D/a$, approximately twice the width $\lambda D/a$ of a secondary bright band.

2. Intensities of bright bands: For two equally illuminated, very narrow slits, the interference maxima have equal intensity when the single-slit diffraction envelope is neglected. In single-slit diffraction, the central maximum is the brightest, and successive secondary maxima have rapidly decreasing intensities.

Step 6: Conclusion Single-slit diffraction results from superposition of secondary waves across the slit: complete cancellation gives minima at $a \sin \theta = \pm n\lambda$, while incomplete cancellation gives the secondary maxima. Their intensities fall with order. Unlike ideal double-slit interference, single-slit diffraction has a central bright band of double width and progressively weaker secondary maxima.

Quick Tip to Solve: Use the exact condition $a \sin \theta = n\lambda$ for single-slit minima, and remember that the central bright width spans both first minima. Secondary-maximum positions with half-integer orders are only approximate.

33(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 uses two converging lenses: the objective forms a real, inverted, enlarged intermediate image, and the eyepiece acts as a simple magnifier for that image.
- A real image is formed by the actual intersection of rays. A screen reveals the image by scattering the incident light; it does not create the convergence.
- A mirror can receive a converging beam, whose prospective meeting point behind the mirror is a virtual object. The mirror formula is $1/f = 1/v + 1/u$, with Cartesian signed distances f, u, v .

Step 1: (i) Describe the construction Two convex lenses are mounted coaxially at the ends of an adjustable tube. The objective O , facing the small object, has a very short focal length and a small aperture. The eyepiece E , close to the eye, has a short focal length but a larger focal length and aperture than the objective. A focusing arrangement varies the object distance or the tube length. The object is illuminated and placed just beyond the objective's first principal focus F_o .

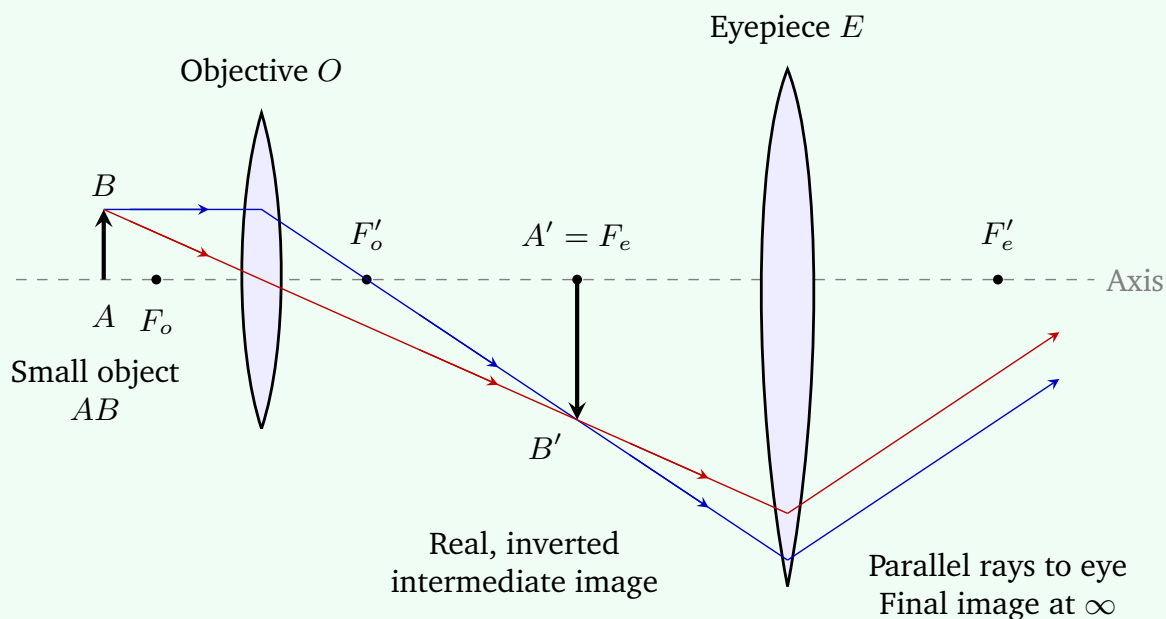
Step 2: (i) Trace the rays and explain the working The objective forms the real, inverted and enlarged image $A'B'$ inside the tube. In the ray diagram, a ray from B parallel to the principal axis refracts through the objective's second focus F'_o ; another ray passes undeviated through its optical centre. Their intersection fixes B' .

For normal adjustment, $A'B'$ lies in the first focal plane of the eyepiece, with A' at F_e . The rays from each point then emerge parallel from the eyepiece, and the relaxed eye sees a final virtual image at infinity. It is highly magnified and inverted relative to the original object. Alternatively, placing $A'B'$ slightly inside the eyepiece's focal length gives a finite virtual image, commonly adjusted to the least distance of distinct vision D .

The magnification occurs in two stages. For normal adjustment, its magnitude is

$$|M| = |m_o|M_e = \frac{|v_o|}{|u_o|} \frac{D}{f_e},$$

where u_o, v_o are the objective's object and image distances and f_e is the eyepiece focal length. Thus the eyepiece further magnifies the enlarged image made by the objective.



Compound microscope in normal adjustment: $A'B'$ lies in the eyepiece focal plane and the final virtual image is at infinity. The schematic is not to scale.

Step 3: (ii)(I) Remove the screen at the real image The image remains at the same location when the screen is removed. For an object between f and $2f$, the convex lens brings rays from each object point to a corresponding real image point beyond $2f$, independently of the screen. After crossing, these rays diverge. An eye placed beyond the image location, in the outgoing beam and suitably focused, can see the image. Removing the screen removes the scattering surface, not the ray intersections.

Step 4: (ii)(II) Supply a virtual object to the mirrors Both mirrors can form real images if the incident light is already converging suitably. For example, a convex lens can first produce a converging beam, and the mirror can intercept it before it reaches its prospective focus behind the mirror. That prospective focus is a virtual object for the mirror.

For a plane mirror, reflection reverses the longitudinal direction of the converging rays, making them actually meet in front of the mirror. With the incident direction positive, the virtual object has $u > 0$. Since $1/f = 0$, the mirror formula gives $v = -u < 0$: a real image at an equal distance in front.

For a convex mirror, $f > 0$, and

$$\frac{1}{v} = \frac{1}{f} - \frac{1}{u}, \quad v = \frac{fu}{u - f}.$$

If the virtual object lies between the pole and the focus behind the mirror, $0 < u < f$, then $v < 0$, so the reflected rays converge to a real image in front. Thus the usual statement that these mirrors give virtual images assumes an ordinary real object; converging incident rays provide the required exception.

Step 5: Conclusion The microscope combines objective enlargement with eyepiece angular magnification to give an inverted, greatly magnified virtual image. A convex lens's real image persists without a screen. Plane and convex mirrors can form real images when supplied with suitable virtual objects; for a convex mirror the virtual object must lie between its pole and focus.

Quick Tip to Solve: In the microscope diagram, first locate the real intermediate image and then put it at the eyepiece focus for parallel emergent rays. For either mirror, test whether the incident beam diverges from a real object or converges towards a virtual one.