

CBSE Class 12 Physics Question Paper 2024 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) Question paper is divided into **FIVE** sections – Section **A, B, C, D** and **E**.
- (iii) In **Section A** : Question number **1** to **16** are Multiple Choice (MCQ) type questions carrying **1** mark each.
- (iv) In **Section B** : Question number **17** to **21** are Very Short Answer (VSA) type questions carrying **2** marks each.
- (v) In **Section C** : Question number **22** to **28** are Short Answer (SA) type questions carrying **3** marks each.
- (vi) In **Section D** : Question number **29 & 30** are Long Answer (LA) type questions carrying **4** marks each.
- (vii) In **Section E** : Question number **31** to **33** are Case-Based questions carrying **5** marks each.
- (viii) There is no overall choice. However, an internal choice has been provided in **1** question in Section–**B**, **1** question in Section–**C**, **2** questions in Section–**D** and **3** questions in Section–**E**.
- (ix) Use of calculators is NOT allowed.

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

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

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

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

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

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

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

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

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

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

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

Section A (16 marks)

1. A battery supplies 0.9 A current through a $2\ \Omega$ resistor and 0.3 A current through a $7\ \Omega$ resistor when connected one by one. The internal resistance of the battery is: [1 mark]

- (A) $2\ \Omega$
- (B) $1.2\ \Omega$
- (C) $1\ \Omega$
- (D) $0.5\ \Omega$

Correct Answer: (D) $0.5\ \Omega$

Solution:

Concept:

- For a cell of emf E and internal resistance r , the current through external resistance R is $I = E/(R + r)$.
- The same battery has the same emf in both connections; equating $I(R + r)$ eliminates E .

Step 1: Write the two circuit equations With all resistances in ohms, the two measurements give

$$E = 0.9(2 + r), \quad E = 0.3(7 + r).$$

The larger load gives the smaller current, as expected for a fixed battery.

Step 2: Eliminate the emf and check the options Equating the two expressions yields

$$1.8 + 0.9r = 2.1 + 0.3r, \quad 0.6r = 0.3.$$

The values 2, 1.2 and $1\ \Omega$ in options (A), (B) and (C) give unequal emfs for the two measurements. The value in (D) gives $E = 2.25\text{ V}$ in both cases.

Step 3: Conclusion The internal resistance is $r = 0.5\ \Omega$. Hence, the correct option is (D).

Quick Tip to Solve: Equate $I_1(R_1 + r) = I_2(R_2 + r)$; do not equate terminal voltages for different loads.

2. A particle of mass m and charge q describes a circular path of radius R in a magnetic field. If its mass and charge were $2m$ and $\frac{q}{2}$ respectively, the radius of its path would be: [1 mark]

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

Correct Answer: (D) $4R$

Solution:

Concept:

- For circular motion perpendicular to a uniform magnetic field, magnetic force supplies the centripetal force: $|q|vB = mv^2/R$.
- Thus $R = mv/(|q|B)$. In comparing the two particles, the speed v and field magnitude B are taken

as unchanged.

Step 1: Express the radius ratio The printed change concerns mass and charge. Under the usual implied condition of equal speed in the same field,

$$\frac{R'}{R} = \frac{m'}{m} \frac{|q|}{|q'|}.$$

The radius depends directly on mass and inversely on the magnitude of charge.

Step 2: Apply both changes Doubling mass multiplies the radius by two; halving charge multiplies it by another two:

$$\frac{R'}{R} = 2 \times 2 = 4.$$

Option (C) accounts for only one change. Options (A) and (B) would reduce the radius, whereas both specified changes increase it. No fixed kinetic energy or accelerating voltage is stated, so those different comparisons should not be introduced.

Step 3: Conclusion The new radius is $4R$, at unchanged speed and magnetic field. Hence, the correct option is (D).

Quick Tip to Solve: At fixed speed and field, compare $m/|q|$; doubling mass and halving charge multiply, giving a factor of four.

3. Which of the following pairs is that of paramagnetic materials?

[1 mark]

- (A) Copper and Aluminium
- (B) Sodium and Calcium
- (C) Lead and Iron
- (D) Nickel and Cobalt

Correct Answer: (B) Sodium and Calcium

Solution:

Concept:

- Paramagnetic materials are weakly attracted by an applied magnetic field and have a small positive magnetic susceptibility χ .
- Diamagnetic materials have negative susceptibility, while ferromagnetic materials such as iron, nickel and cobalt show strong magnetic ordering.

Step 1: Classify the proposed pair Sodium and calcium are standard examples of paramagnetic materials. Both are weakly attracted toward a stronger magnetic field, so both members of option (B) belong to the required class.

Step 2: Eliminate the other pairs In option (A), aluminium is paramagnetic but copper is diamagnetic; one correct member does not make the pair correct. In option (C), lead is diamagnetic and iron is ferromagnetic. In option (D), nickel and cobalt are both ferromagnetic, so their strong attraction

should not be confused with paramagnetism.

Step 3: Conclusion Sodium and calcium form the paramagnetic pair. Hence, the correct option is (B).

Quick Tip to Solve: Check both members of a materials pair; remember iron, cobalt and nickel together as the common ferromagnets.

4. A galvanometer of resistance $50\ \Omega$ is converted into a voltmeter of range (0-2 V) using a resistor of $1.0\text{ k}\Omega$. If it is to be converted into a voltmeter of range (0-10 V), the resistance required will be: [1 mark]

- (A) $4.8\text{ k}\Omega$
- (B) $5.0\text{ k}\Omega$
- (C) $5.2\text{ k}\Omega$
- (D) $5.4\text{ k}\Omega$

Correct Answer: (C) $5.2\text{ k}\Omega$

Solution:

Concept:

- A galvanometer becomes a voltmeter by adding a high resistance R_s in series with its resistance G .
- The full-scale voltage is $V = I_g(G + R_s)$, where the full-scale galvanometer current I_g stays fixed when the voltage range changes.

Step 1: Obtain the full-scale current For the initial range, $G = 50\ \Omega$, $R_s = 1000\ \Omega$ and $V = 2\text{ V}$. Hence,

$$I_g = \frac{2}{1000 + 50} = \frac{2}{1050}\text{ A}.$$

Include the galvanometer resistance when calculating the total resistance.

Step 2: Calculate the new series resistance At the same current, the new total resistance for 10 V is

$$G + R'_s = \frac{10}{2/1050} = 5250\ \Omega.$$

Subtract G to obtain the external resistor: $R'_s = 5250 - 50 = 5200\ \Omega$. Simply multiplying the old external resistor by five gives option (B), which neglects the fixed galvanometer resistance. Options (A) and (D) also fail the required total-resistance ratio of five.

Step 3: Conclusion The required series resistance is $5.2\text{ k}\Omega$. Hence, the correct option is (C).

Quick Tip to Solve: Scale the total voltmeter resistance with the range, then subtract the unchanged galvanometer resistance.

5. Two coils are placed near each other. When the current in one coil is changed at the rate of 5 A/s, an emf of 2 mV is induced in the other. The mutual inductance of the two coils is: [1 mark]

- (A) 0.4 mH
- (B) 2.5 mH
- (C) 10 mH
- (D) 2.5 H

Correct Answer: (A) 0.4 mH

Solution:

Concept:

- Mutual induction produces an emf in one coil when the current in a nearby coil changes: $\varepsilon = -M dI/dt$.
- The mutual inductance M is obtained from magnitudes, $M = |\varepsilon|/|dI/dt|$; its SI unit is the henry, $H = V s A^{-1}$.

Step 1: Convert the emf to volts The induced emf magnitude is $2 \text{ mV} = 2 \times 10^{-3} \text{ V}$, and the rate of current change is 5 A s^{-1} . The minus sign in Faraday's law specifies opposition to the change; it does not make the inductance magnitude negative.

Step 2: Divide emf by the current-change rate Substitution gives

$$M = \frac{2 \times 10^{-3}}{5} \text{ H} = 0.4 \times 10^{-3} \text{ H}.$$

Option (B) comes from reversing the numerical ratio, while (C) comes from multiplying instead of dividing. The value 2.5 H in (D) has the wrong scale and does not reproduce the measured emf.

Step 3: Conclusion The mutual inductance is 0.4 mH. Hence, the correct option is (A).

Quick Tip to Solve: Dividing emf in millivolts by a current-change rate in amperes per second gives mutual inductance directly in millihenries.

6. The electromagnetic waves used to purify water are: [1 mark]

- (A) Infrared rays
- (B) Ultraviolet rays
- (C) X-rays
- (D) Gamma rays

Correct Answer: (B) Ultraviolet rays

Solution:

Concept:

- Electromagnetic waves have different uses according to their wavelength and interaction with matter; photon energy increases with frequency, $E = h\nu$.
- Ultraviolet radiation has a germicidal action and is used to disinfect water by inactivating microorganisms.

Step 1: Identify the required effect In this application, purification refers to disinfection. Ultraviolet radiation damages the genetic material of microorganisms, preventing their reproduction. This makes

ultraviolet lamps suitable for water-disinfection systems; the radiation does not need to remove dissolved salts to perform that function.

Step 2: Distinguish the other uses Infrared rays primarily produce heating and are not the standard radiation used here. X-rays are commonly associated with imaging, while gamma rays are used in applications such as irradiation and radiotherapy. Although sufficiently energetic radiation can damage cells, options (C) and (D) do not describe the standard CBSE water-purification application.

Step 3: Conclusion Ultraviolet rays are used to purify water by disinfection. Hence, the correct option is (B).

Quick Tip to Solve: Associate ultraviolet with germicidal water disinfection and infrared with heating when matching spectrum uses.

7. The focal lengths of the objective and the eyepiece of a compound microscope are 1 cm and 2 cm respectively. If the tube length of the microscope is 10 cm, the magnification obtained by the microscope for most suitable viewing by relaxed eye is: [1 mark]

- (A) 250
- (B) 200
- (C) 150
- (D) 125

Correct Answer: (D) 125

Solution:

Concept:

- For relaxed-eye viewing, a compound microscope forms its final image at infinity. The eyepiece angular magnification is D/f_e , where $D = 25$ cm is the least distance of distinct vision.
- In the standard microscope approximation, the objective magnification magnitude is L/f_o , so the total magnification is $M = (L/f_o)(D/f_e)$.

Step 1: Choose the relaxed-eye formula Here $f_o = 1$ cm, $f_e = 2$ cm and $L = 10$ cm. The phrase “relaxed eye” selects the final image at infinity. Therefore use D/f_e , rather than the near-point eyepiece factor $1 + D/f_e$.

Step 2: Multiply the two magnifications Using all lengths in centimetres makes each ratio dimensionless:

$$|m_o| \simeq \frac{10}{1} = 10, \quad m_e = \frac{25}{2} = 12.5.$$

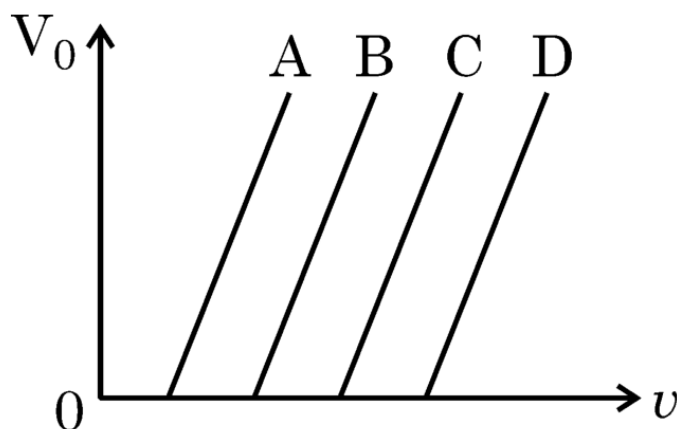
Thus their product is $10 \times 12.5 = 125$. Options (A), (B) and (C) do not equal the product for the given focal lengths and tube length. The objective inverts the image, but the positive options ask for the magnitude of magnification.

Step 3: Conclusion The magnification magnitude for relaxed-eye viewing is 125. Hence, the correct option is (D).

Quick Tip to Solve: “Relaxed eye” means the final image is at infinity: use $(L/f_o)(D/f_e)$, with no added one in the eyepiece factor.

8. The variation of the stopping potential (V_0) with the frequency (ν) of the incident radiation for four metals A, B, C and D is shown in the figure. For the same frequency of incident radiation producing photo-electrons in all metals, the kinetic energy of photo-electrons will be maximum for metal:

[1 mark]



- (A) A
- (B) B
- (C) C
- (D) D

Correct Answer: (A) A

Solution:

Concept:

- Einstein's photoelectric equation is $K_{\max} = h\nu - \phi$, where h is Planck's constant, ν is incident frequency and ϕ is the metal's work function.
- The stopping potential measures the maximum kinetic energy: $K_{\max} = eV_0$. The threshold frequency is $\nu_0 = \phi/h$.

Step 1: Compare the threshold frequencies The horizontal intercept of each line gives its threshold frequency. The graph shows $\nu_{0A} < \nu_{0B} < \nu_{0C} < \nu_{0D}$, so metal A has the smallest work function. All four lines have the same slope h/e .

Step 2: Compare energies at the same frequency For a common frequency above all four thresholds, $h\nu$ is identical for every metal. Subtracting the smallest work function leaves the largest maximum kinetic energy. Equivalently, a vertical line at this frequency meets A's extended line at the greatest stopping potential. B, C and D have progressively larger work functions and therefore smaller maximum kinetic energies.

Step 3: Conclusion The maximum kinetic energy of photo-electrons is greatest for metal A. Hence, the correct option is (A).

Quick Tip to Solve: At a fixed frequency, choose the leftmost threshold intercept: it gives the smallest work function and largest stopping potential.

9. The energy of an electron in the ground state of hydrogen atom is -13.6 eV . The kinetic and potential energy of the electron in the first excited state will be: [1 mark]

(A) -13.6 eV , 27.2 eV

(B) -6.8 eV , 13.6 eV

(C) 3.4 eV , -6.8 eV

(D) 6.8 eV , -3.4 eV

Correct Answer: (C) 3.4 eV , -6.8 eV

Solution:

Concept:

- Hydrogen has energy levels $E_n = -13.6/n^2 \text{ eV}$, where n is the principal quantum number. The first excited state has $n = 2$.
- For a Coulomb-bound electron, potential energy $U = -2K$ and total energy $E = K + U = -K$, where K denotes kinetic energy.

Step 1: Calculate the excited-state total energy Use $n = 2$, rather than the ground-state value $n = 1$:

$$E_2 = \frac{-13.6}{2^2} = -3.4 \text{ eV}.$$

This negative value is the total energy relative to a free electron at infinity; it is not the kinetic energy.

Step 2: Separate kinetic and potential energies Since $K = -E_2$ and $U = 2E_2$,

$$K = 3.4 \text{ eV}, \quad U = -6.8 \text{ eV}.$$

Their sum is -3.4 eV , as required. Options (A) and (B) incorrectly give negative kinetic energy. Option (D) reverses the required magnitudes and does not satisfy $U = -2K$.

Step 3: Conclusion The kinetic and potential energies are respectively 3.4 eV and -6.8 eV . Hence, the correct option is (C).

Quick Tip to Solve: For a hydrogen orbit, first find the negative total energy, then use the ratio $K : U : E = 1 : -2 : -1$.

10. A Young's double-slit experimental set up is kept in a medium of refractive index $\left(\frac{4}{3}\right)$. Which maximum in this case will coincide with the 6th maximum obtained if the medium is replaced by air? [1 mark]

- (A) 4th
- (B) 6th
- (C) 8th
- (D) 10th

Correct Answer: (C) 8th

Solution:

Concept:

- At fixed frequency, wavelength in a medium of refractive index μ is $\lambda_m = \lambda_a / \mu$, where λ_a is the wavelength in air.
- The position of the n th bright fringe is $y_n = n\lambda D/d$, with screen distance D and slit separation d .

Step 1: Equate the two fringe positions Let the n th maximum in the medium coincide with the sixth maximum in air. With the same slit geometry, their distances from the central maximum satisfy

$$n \frac{\lambda_a}{\mu} \frac{D}{d} = 6 \lambda_a \frac{D}{d}.$$

Cancelling the common factors gives $n/\mu = 6$.

Step 2: Substitute the printed refractive index The official question gives $\mu = 4/3$. Therefore,

$$n = 6\mu = 6 \times \frac{4}{3} = 8.$$

The medium reduces fringe spacing to three-quarters of its air value, so a higher order reaches the same position. The fourth and sixth orders are too low; the tenth lies beyond the specified air fringe.

Step 3: Conclusion The eighth maximum in the medium coincides with the sixth maximum in air. Hence, the correct option is (C).

Quick Tip to Solve: At a fixed screen position, bright-fringe order increases by the refractive index: $n_m = \mu n_a$.

11. The potential energy between two nucleons inside a nucleus is minimum at a distance of about:

[1 mark]

- (A) 0.8 fm
- (B) 1.6 fm
- (C) 2.0 fm
- (D) 2.8 fm

Correct Answer: (A) 0.8 fm

Solution:

Concept:

- The nuclear interaction has a short-range attractive region and a strongly repulsive core. Its potential energy $U(r)$ depends on the separation r of the nucleons.
- The radial force is $F_r = -dU/dr$. At the bottom of the potential well, $dU/dr = 0$, so the attractive and repulsive tendencies balance.

Step 1: Identify the bottom of the nuclear potential well In the standard nuclear potential-energy curve, the energy decreases as two well-separated nucleons approach, reaches its most negative value near $r_0 = 0.8$ fm, and rises sharply at smaller separations because of the repulsive core.

Step 2: Distinguish the minimum from the force range The question asks for the separation at minimum potential energy, not the maximum distance over which nuclear attraction can act. Values such as 1.6 fm, 2.0 fm and 2.8 fm lie farther out than the bottom of this standard potential well. Recall that $1 \text{ fm} = 10^{-15} \text{ m}$.

Step 3: Conclusion The potential energy is minimum at approximately 0.8 fm. Hence, the correct option is (A).

Quick Tip to Solve: Associate the nuclear potential minimum with about 0.8 fm; do not confuse it with the larger range of nuclear attraction.

12. A pure Si crystal having $5 \times 10^{28} \text{ atoms m}^{-3}$ is doped with 1 ppm concentration of antimony. If the concentration of holes in the doped crystal is found to be $4.5 \times 10^9 \text{ m}^{-3}$, the concentration (in m^{-3}) of intrinsic charge carriers in Si crystal is about:

[1 mark]

- (A) 1.2×10^{15}
- (B) 1.5×10^{16}
- (C) 3.0×10^{15}
- (D) 2.0×10^{16}

Correct Answer: (B) 1.5×10^{16}

Solution:

Concept:

- Pentavalent antimony is a donor impurity in silicon. Each ionised donor supplies one conduction electron, so the electron concentration n is approximately the donor concentration N_D .
- At thermal equilibrium, the mass-action law is $np = n_i^2$, where p is the hole concentration and n_i is the intrinsic electron (or hole) concentration.

Step 1: Convert the impurity concentration One part per million means one donor per 10^6 silicon

atoms. Assuming the usual complete donor ionisation,

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

Charge neutrality gives $n = N_D + p$. Since the given $p = 4.5 \times 10^9 \text{ m}^{-3}$ is negligible beside N_D , use $n \simeq 5 \times 10^{22} \text{ m}^{-3}$.

Step 2: Apply the mass-action law The intrinsic concentration is the geometric mean of the doped electron and hole concentrations:

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

Squaring this result recovers $2.25 \times 10^{32} \text{ m}^{-6}$; none of the other three options does. The intrinsic concentration means either species separately, since intrinsic silicon has equal electron and hole concentrations.

Step 3: Conclusion The intrinsic charge-carrier concentration is approximately $1.5 \times 10^{16} \text{ m}^{-3}$. Hence, the correct option is (B).

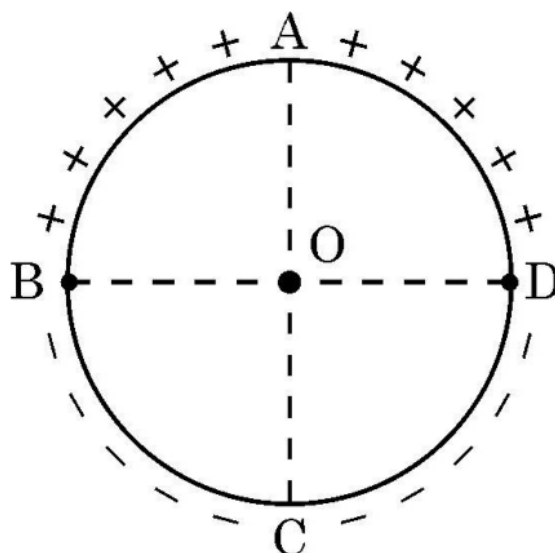
Quick Tip to Solve: Convert ppm to 10^{-6} before finding donor density, then use $n_i = \sqrt{N_D p}$; rewrite the power of ten as an even power before taking the root.

13. For Questions 13 to 16, two statements are given — one labelled Assertion (A) and other labelled Reason (R). Select the correct answer to these questions from the options as given below:

Assertion (A): Equal amount of positive and negative charges are distributed uniformly on two halves of a thin circular ring as shown in figure. The resultant electric field at the centre O of the ring is along OC.

Reason (R): It is so because the net potential at O is not zero.

[1 mark]



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

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

Solution:

Concept:

- Electric field is a vector: fields point away from positive charges and toward negative charges. Symmetry determines which components cancel.
- Electric potential is a scalar, $V = \sum kq/r$, where $k = 1/(4\pi\epsilon_0)$. Equal opposite charges at equal distances give cancelling potentials.

Step 1: Evaluate the Assertion The upper semicircle carries positive charge. At O, its leftward and rightward field components cancel in symmetric pairs, while its downward components add. The lower negative semicircle also produces a downward field at O, toward its charges. Thus the total field points downward along OC and the Assertion is true.

Step 2: Evaluate the Reason Let the charges on the two halves be $+Q$ and $-Q$, and let the common ring radius be R . Every charge element is the same distance from O, so

$$V_O = \frac{kQ}{R} + \frac{k(-Q)}{R} = 0.$$

The Reason claims that the potential at O is not zero, so it is false.

Step 3: Test the proposed explanation The field direction follows from vector addition and symmetry, not from a nonzero potential at that point. A zero value of potential does not imply zero field: field depends on the spatial gradient of potential. Options (A) and (B) require a true Reason, and option (D) requires a false Assertion, so those combinations do not apply.

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

Quick Tip to Solve: For opposite semicircular charges, add fields as vectors but potentials as signed scalars: the central fields reinforce while the potentials cancel.

14. Assertion (A): The energy of a charged particle moving in a magnetic field does not change.

Reason (R): It is because the work done by the magnetic force on the charge moving in a magnetic field is zero. [1 mark]

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

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

Solution:

Concept:

- A charge q moving with velocity $\vec{v}$ in a magnetic field $\vec{B}$ experiences magnetic force $\vec{F}_B = q(\vec{v} \times \vec{B})$, perpendicular to its velocity.
- Instantaneous power is $P = \vec{F} \cdot \vec{v}$. By the work-energy theorem, a force changes kinetic energy only when it does work.

Step 1: Evaluate the Assertion The magnetic force can change the direction of a charged particle's velocity, but cannot change its speed. Consequently, its kinetic energy $K = mv^2/2$ remains constant under the action of the magnetic field alone. The Assertion is true in this stated magnetic-force context.

Step 2: Evaluate the Reason During a short time dt , displacement is $d\vec{r} = \vec{v} dt$. Hence,

$$dW_B = \vec{F}_B \cdot d\vec{r} = q(\vec{v} \times \vec{B}) \cdot \vec{v} dt = 0.$$

The scalar product vanishes because the cross product is perpendicular to $\vec{v}$. Thus the magnetic force does zero work and the Reason is true.

Step 3: Connect work with the energy change Applying the work-energy theorem gives $\Delta K = W_B = 0$. Zero magnetic work directly explains the unchanged energy, so the two true statements are causally connected. Option (B) wrongly denies this explanation, while options (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: Test magnetic work using $(\vec{v} \times \vec{B}) \cdot \vec{v} = 0$: a force perpendicular to motion turns the velocity without changing its magnitude.

15. Assertion (A): In a Young's double-slit experiment, interference pattern is not observed when two coherent sources are infinitely close to each other.

Reason (R): The fringe width is proportional to the separation between the two sources. [1 mark]

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

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

Solution:

Concept:

- In Young's experiment, the fringe width is $\beta = \lambda D/d$, where λ is the wavelength, D the screen distance and d the slit separation.
- Distinct fringes require a path difference that varies appreciably across the screen.

Step 1: Evaluate the assertion As the coherent sources become infinitely close, $d \rightarrow 0$ and $\beta \rightarrow \infty$. Bright and dark bands therefore cannot be resolved on a finite screen. For coincident sources, the geometrical path difference is the same everywhere. Thus Assertion (A) is true in the stated limiting sense.

Step 2: Evaluate the reason The formula gives $\beta \propto 1/d$ for fixed λ and D . The fringe width is inversely proportional to the source separation, not directly proportional. Therefore Reason (R) is false.

Step 3: Check the explanation and options A false reason cannot explain the true assertion. Options (A) and (B) require both statements to be true, while option (D) incorrectly declares the assertion

false.

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

Quick Tip to Solve: Write $\beta = \lambda D/d$ first: bringing the slits closer spreads the fringes farther apart.

16. Assertion (A): An alpha particle is moving towards a gold nucleus. The impact parameter is maximum for the scattering angle of 180° .

Reason (R): The impact parameter in an alpha particle scattering experiment does not depend upon the atomic number of the target nucleus. [1 mark]

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

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

Solution:

Concept:

- The impact parameter b is the perpendicular distance from the nucleus to the initial straight-line path of an alpha particle.
- Rutherford scattering gives $b = \frac{kZe^2}{K} \cot(\theta/2)$, where the alpha charge is $2e$, the target charge is Ze , K is incident kinetic energy and $k = 1/(4\pi\epsilon_0)$.

Step 1: Evaluate the assertion A deflection of 180° is a head-on encounter. Substituting $\theta = 180^\circ$ gives $b = (kZe^2/K) \cot 90^\circ = 0$. This is the minimum impact parameter, not the maximum. Therefore the assertion is false.

Step 2: Evaluate the reason At a specified scattering angle and incident kinetic energy, $b \propto Z$. The impact parameter needed to produce that deflection depends on the atomic number through the nuclear electrostatic repulsion. Thus the reason is false.

Step 3: Check the explanation and options Since both statements are false, the reason cannot explain the assertion. Options (A) and (B) require both statements to be true, and option (C) requires a true assertion, so none applies.

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

Quick Tip to Solve: Associate backscattering through 180° with a head-on path: its impact parameter is exactly zero.

Section B (10 marks)

17(a). Four point charges of $1\ \mu\text{C}$, $-2\ \mu\text{C}$, $1\ \mu\text{C}$ and $-2\ \mu\text{C}$ are placed at the corners A, B, C and D respectively, of a square of side 30 cm. Find the net force acting on a charge of $4\ \mu\text{C}$ placed at the centre of the square. [2 marks]

Solution:

Concept:

- Coulomb's law gives the magnitude $F = k|qQ|/r^2$, where r is the separation and $k = 9 \times 10^9\ \text{N m}^2\text{C}^{-2}$.
- The net force is the vector sum of individual forces. Equal charges at opposite corners of a square produce equal and opposite forces at its centre.

Step 1: Find the common distance from the centre Let O be the centre and $a = 0.30\ \text{m}$ the side. Each corner is half a diagonal away, so

$$r = \frac{a}{\sqrt{2}}, \quad r^2 = \frac{(0.30)^2}{2} = 0.045\ \text{m}^2.$$

The test charge is $Q = 4 \times 10^{-6}\ \text{C}$. Corners A and C are opposite, as are B and D.

Step 2: Add the forces from each opposite pair Charges at A and C are both positive and repel the test charge along the diagonal AC in opposite directions. Each force has magnitude

$$F_A = F_C = \frac{9 \times 10^9 (1 \times 10^{-6})(4 \times 10^{-6})}{0.045} = 0.80\ \text{N}.$$

Charges at B and D are both negative and attract the test charge along diagonal BD in opposite directions. Their equal magnitudes are $F_B = F_D = 1.60\ \text{N}$. Consequently, $\vec{F}_A + \vec{F}_C = \vec{0}$ and $\vec{F}_B + \vec{F}_D = \vec{0}$. The unequal magnitudes between the two pairs do not matter, because each pair cancels separately.

Step 3: Conclusion The net force on the $4\ \mu\text{C}$ charge at the centre is $\boxed{\vec{F}_{\text{net}} = \vec{0}}$, of magnitude $\boxed{0\ \text{N}}$.

Quick Tip to Solve: Pair opposite corners first: identical charges at equal distances cancel at the centre regardless of the other pair's magnitude.

OR

17(b). Three point charges, $1\ \mu\text{C}$ each, are kept at the vertices of an equilateral triangle of side 10 cm. Find the net electric field at the centroid of triangle. [2 marks]

Solution:

Concept:

- The electric field of a positive point charge q has magnitude $E = kq/r^2$ and points away from the charge; $k = 1/(4\pi\epsilon_0)$.
- The centroid of an equilateral triangle is equidistant from its vertices. The three vertex-to-centroid directions are separated by 120° .

Step 1: Find the field magnitude from each charge Let the side be $a = 0.10\ \text{m}$ and each charge

$q = 1 \times 10^{-6}$ C. The centroid lies two-thirds of the way along each median from its vertex. Since the median is $\sqrt{3}a/2$, the distance from a vertex is $r = a/\sqrt{3}$. Hence each field has the same magnitude,

$$E = \frac{kq}{r^2} = \frac{3kq}{a^2} = \frac{3(9 \times 10^9)(10^{-6})}{(0.10)^2} = 2.7 \times 10^6 \text{ N C}^{-1}.$$

Step 2: Resolve and add the three equal fields Choose the positive x -axis along the field due to one charge. The other fields make angles 120° and 240° with this axis. Their vector components satisfy

$$\begin{aligned} E_x &= E + E \cos 120^\circ + E \cos 240^\circ = E - E/2 - E/2 = 0, \\ E_y &= E \sin 120^\circ + E \sin 240^\circ = 0. \end{aligned}$$

The cancellation follows from equal field magnitudes and the symmetric directions; their scalar magnitudes must not be added.

Step 3: Conclusion The net electric field at the centroid is $\vec{E}_{\text{net}} = \vec{0}$, of magnitude 0 N C^{-1} .

Quick Tip to Solve: Three equal vectors spaced by 120° have zero sum; recognise this symmetry at an equilateral triangle's centroid.

18. Derive an expression for magnetic force $\vec{F}$ acting on a straight conductor of length L carrying current I in an external magnetic field $\vec{B}$. Is it valid when the conductor is in zig-zag form? Justify.

[2 marks]

Solution:

Concept:

- The magnetic force on a moving charge is $\vec{f} = q\vec{v} \times \vec{B}$. For a steady current, the random thermal velocities average to zero and the drift motion contributes to the net force.
- If n is the electron number density, A the cross-sectional area and v_d the drift speed, the conventional current magnitude is $I = neAv_d$.

Step 1: Sum the forces on the charge carriers Consider a straight length L in a uniform external field $\vec{B}$. It contains $N = nAL$ conduction electrons. Let $\hat{\ell}$ point along conventional current, so each electron has charge $-e$ and drift velocity $-v_d\hat{\ell}$. The total magnetic force transferred to the conductor is

$$\begin{aligned} \vec{F} &= N(-e)(-v_d\hat{\ell}) \times \vec{B} \\ &= neAv_dL\hat{\ell} \times \vec{B} = I\vec{L} \times \vec{B}, \end{aligned}$$

where $\vec{L} = L\hat{\ell}$. Thus the magnitude is $F = ILB \sin \theta$, with θ the angle between current and field; the right-hand rule gives the force direction.

Step 2: Apply the law to a zig-zag conductor The local law $d\vec{F} = I d\vec{\ell} \times \vec{B}$ remains valid. For a zig-zag wire carrying the same steady current in a uniform field, add the vector forces on its straight segments:

$$\vec{F}_{\text{net}} = I \left(\sum_j \vec{L}_j \right) \times \vec{B} = I(\vec{r}_{\text{end}} - \vec{r}_{\text{start}}) \times \vec{B}.$$

Hence the same vector form holds with the end-to-end displacement directed along current, not with the total bent-wire length. If the field is nonuniform, $\vec{B}$ cannot be taken outside the integral and the

force must be evaluated segment by segment.

Step 3: Conclusion For a straight conductor, $\vec{F} = I\vec{L} \times \vec{B}$. For a zig-zag conductor in a uniform field, replace $\vec{L}$ by its end-to-end displacement; using the total wire length in this formula is not valid.

Quick Tip to Solve: For a bent wire in a uniform field, join its endpoints in the current direction and use that displacement vector in the cross product.

19. A telescope has an objective lens of focal length 150 cm and an eyepiece of focal length 5 cm. Calculate its magnifying power in normal adjustment and the distance of the image formed by the objective. [2 marks]

Solution:

Concept:

- For an astronomical telescope in normal adjustment, the distant object and the final image are both effectively at infinity. The objective forms a real intermediate image at its focal plane.
- The angular magnification is $M = -f_o/f_e$, where f_o and f_e are the positive focal lengths of the objective and eyepiece. The negative sign indicates inversion.

Step 1: Calculate the angular magnification The objective has $f_o = 150$ cm, and the eyepiece has $f_e = 5$ cm. Their ratio is dimensionless because both lengths are in the same unit:

$$M = -\frac{150}{5} = -30.$$

Thus the telescope increases the angular size by a factor of 30, and the image is inverted relative to the distant object.

Step 2: Locate the image formed by the objective Parallel rays from the distant object converge at the objective's principal focal plane. Equivalently, the lens formula with $u \rightarrow -\infty$ gives

$$\frac{1}{v_o} - \frac{1}{u} = \frac{1}{f_o} \Rightarrow v_o = f_o = 150 \text{ cm}.$$

This real intermediate image lies on the eyepiece side of the objective and is also at the first focal plane of the eyepiece, 5 cm in front of it. The lens separation is consequently 155 cm; this is distinct from the requested objective-image distance.

Step 3: Conclusion The magnifying power has magnitude 30 (signed angular magnification $M = -30$). The objective forms its image 150 cm from the objective, towards the eyepiece.

Quick Tip to Solve: In normal adjustment, use the focal-length ratio for magnifying power and f_o alone for the objective-image distance; $f_o + f_e$ is the tube length.

20(a). Two energy levels of an electron in hydrogen atom are separated by 2.55 eV. Find the wavelength of radiation emitted when the electron makes transition from the higher energy level to the lower energy level. [2 marks total]

Solution:

Concept:

- The emitted photon carries the energy difference ΔE between the two atomic levels: $\Delta E = h\nu = hc/\lambda$, where h is Planck's constant and c is the speed of light.
- The wavelength is inversely proportional to the photon energy: $\lambda = hc/\Delta E$. Convert electron volts to joules before substituting SI constants.

Step 1: Convert the energy difference to SI units The electron loses energy while moving to the lower level. This energy becomes the energy of the emitted photon. Since $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$, the positive gap is

$$\Delta E = 2.55 \times 1.6 \times 10^{-19} = 4.08 \times 10^{-19} \text{ J}.$$

Step 2: Apply the photon energy relation Using $h = 6.63 \times 10^{-34} \text{ J s}$ and $c = 3.0 \times 10^8 \text{ m s}^{-1}$,

$$\lambda = \frac{hc}{\Delta E} = \frac{(6.63 \times 10^{-34})(3.0 \times 10^8)}{4.08 \times 10^{-19}} = 4.875 \times 10^{-7} \text{ m}.$$

This wavelength is in the visible region. More precise constants give approximately 486 nm; the small numerical difference is due to the rounded constants.

Step 3: Conclusion The emitted wavelength is approximately $4.88 \times 10^{-7} \text{ m}$, or 488 nm, using the stated rounded constants.

Quick Tip to Solve: For photon wavelengths, first convert the energy gap from eV to J, then divide hc by that positive gap.

20(b). In which series of hydrogen spectrum this line shall fall?

Solution:

Concept:

- Hydrogen has energy levels $E_n = -13.6/n^2 \text{ eV}$. Transitions ending at $n = 2$ form the Balmer series.
- The energy emitted in a hydrogen transition is $\Delta E = 13.6(1/n_f^2 - 1/n_i^2) \text{ eV}$, where $n_i > n_f$.

Step 1: Match the stated energy gap to hydrogen levels The line is the radiation from the 2.55 eV gap in part (a). For $n_i = 4$ and $n_f = 2$,

$$E_4 - E_2 = 13.6 \left(\frac{1}{2^2} - \frac{1}{4^2} \right) = 13.6 \times \frac{3}{16} = 2.55 \text{ eV}.$$

Thus these levels reproduce the given energy difference exactly.

Step 2: Identify the series by the final level Hydrogen series are named by their final energy level,

not by the initial one. The matching transition ends at $n_f = 2$, whose lines form the Balmer series. A transition ending at $n = 1$ belongs to Lyman, whereas one ending at $n = 3$ belongs to Paschen.

Step 3: Conclusion The line belongs to the Balmer series and corresponds to the $n = 4 \rightarrow n = 2$ transition.

Quick Tip to Solve: Identify a hydrogen series from the final level: $n_f = 2$ means Balmer. Check the proposed levels by reproducing the given energy gap.

21. The earth revolves around the sun in an orbit of radius 1.5×10^{11} m with orbital speed 30 km/s. Find the quantum number that characterises its revolution using Bohr's model in this case (mass of earth = 6.0×10^{24} kg). [2 marks]

Solution:

Concept:

- Bohr's angular-momentum condition is $L = mvr = n\hbar = nh/(2\pi)$, where m , v and r are the orbiting body's mass, speed and orbital radius, and n is the principal quantum number.
- Apply this condition formally to the Earth's revolution, using SI units throughout. The resulting enormous quantum number illustrates the classical limit of macroscopic orbital motion.

Step 1: Convert the speed and calculate the orbital angular momentum The given quantities are $m = 6.0 \times 10^{24}$ kg, $r = 1.5 \times 10^{11}$ m, and

$$v = 30 \text{ km s}^{-1} = 3.0 \times 10^4 \text{ m s}^{-1}.$$

For a circular orbit the velocity is perpendicular to the radius, so the angular momentum magnitude is

$$L = mvr = (6.0 \times 10^{24})(3.0 \times 10^4)(1.5 \times 10^{11}) = 2.7 \times 10^{40} \text{ kg m}^2 \text{ s}^{-1}.$$

Step 2: Apply Bohr's quantisation condition Rearranging $mvr = nh/(2\pi)$ and using $h = 6.63 \times 10^{-34}$ J s gives

$$n = \frac{2\pi mvr}{h} = \frac{2\pi(2.7 \times 10^{40})}{6.63 \times 10^{-34}} \approx 2.56 \times 10^{74}.$$

Angular momentum and h have the same dimensions, so n is dimensionless. Its huge value makes the relative separation between neighbouring allowed angular momenta, $1/n$, negligible. The rounded orbital data determine an approximate value rather than an exact integer.

Step 3: Conclusion The formal Bohr quantum number for the Earth's revolution is $n \approx 2.6 \times 10^{74}$ (dimensionless).

Quick Tip to Solve: Convert kilometres per second to metres per second first, then use $n = 2\pi mvr/h$; omitting 2π confuses h with $\hbar$.

Section C (21 marks)

22(a). Write Einstein's photoelectric equation. How did Millikan prove the validity of this equation?

[3 marks total]

Solution:

Concept:

- Light of frequency ν carries energy in photons of energy $h\nu$. In the photoelectric effect, one electron absorbs one photon.
- The work function ϕ is the minimum energy needed to liberate an electron from a given surface. The remaining photon energy can become the electron's kinetic energy.
- The stopping potential V_s measures the maximum kinetic energy: $K_{\max} = eV_s$, where e is the positive magnitude of electronic charge.

Step 1: Write Einstein's energy equation Energy conservation for an electron escaping with maximum kinetic energy gives

$$h\nu = \phi + K_{\max} = \phi + \frac{1}{2}m_e v_{\max}^2.$$

Here m_e is the electron mass and $v_{\max}$ is the greatest emitted-electron speed. Electrons losing energy inside the surface emerge with smaller kinetic energies. Substituting $K_{\max} = eV_s$ gives $eV_s = h\nu - \phi$.

Step 2: Describe Millikan's experimental verification Millikan illuminated a clean metal surface with monochromatic light of different known frequencies. For each frequency he varied the opposing potential until the photocurrent just became zero and measured that stopping potential. Einstein's equation predicts

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

His graph of V_s against ν was a straight line. Its slope gave h/e , yielding a value of h consistent with Planck's constant, while its frequency-axis intercept gave the threshold frequency. These observations verified the equation quantitatively.

Step 3: Conclusion Einstein's equation is $h\nu = \phi + K_{\max}$. Millikan verified it by measuring the linear stopping-potential versus frequency relation with slope h/e , obtaining Planck's constant consistently.

Quick Tip to Solve: Rewrite the equation as $V_s = (h/e)\nu - \phi/e$: the slope tests Planck's constant and the frequency-axis intercept immediately gives ν_0 .

22(b). Explain the existence of threshold frequency of incident radiation for photoelectric emission from a given surface.

Solution:

Concept:

- Light of frequency ν carries energy in photons of energy $h\nu$. In the photoelectric effect, one electron absorbs one photon.
- The work function ϕ is the minimum energy needed to liberate an electron from a given surface. The remaining photon energy can become the electron's kinetic energy.

Step 1: Apply the minimum escape-energy condition An electron at the surface must obtain at least the work function ϕ from one incident photon. Conservation of energy gives $K_{\max} = h\nu - \phi$, which

can describe emission only if $K_{\max} \geq 0$. At the limiting frequency ν_0 , the fastest electrons have zero kinetic energy:

$$h\nu_0 = \phi, \quad \nu_0 = \frac{\phi}{h}.$$

The threshold therefore depends on the emitting surface through its work function.

Step 2: Explain why lower frequencies cannot eject electrons For $\nu < \nu_0$, each photon has energy $h\nu < \phi$, insufficient to release an electron. Increasing intensity increases the number of incident photons, but their individual energies remain unchanged; it therefore cannot produce ordinary photoelectric emission below threshold. For $\nu > \nu_0$, the energy remaining after escape appears as maximum kinetic energy,

$$K_{\max} = h(\nu - \nu_0).$$

Step 3: Conclusion A threshold frequency exists because each electron needs the minimum escape energy ϕ . Its value is $\nu_0 = \phi/h$; radiation below this frequency cannot cause ordinary photoelectric emission from that surface.

Quick Tip to Solve: To find the threshold, set $K_{\max} = 0$ in Einstein's equation; then compare the energy per photon with the work function.

23(a). Define the term 'electric flux' and write its dimensions.

[3 marks total]

Solution:

Concept:

- Electric flux through a surface measures the electric field passing normally through that surface: $\Phi_E = \int_S \vec{E} \cdot d\vec{A}$, where $d\vec{A} = \hat{n} dA$ is the oriented area element.
- For a uniform electric field and a plane surface, $\Phi_E = \vec{E} \cdot \vec{A} = EA \cos \theta$, where θ is the angle between the field and the surface normal.

Step 1: Define electric flux Electric flux is the surface integral of the normal component of electric field over the surface. For a uniform field through a plane surface, it is the scalar product of the electric field vector and the area vector.

Step 2: Derive the dimensional formula Since electric field is force per unit charge and charge has dimensions $[IT]$,

$$[E] = \frac{[MLT^{-2}]}{[IT]} = [MLT^{-3}I^{-1}].$$

Multiplying by area gives

$$[\Phi_E] = [E][A] = [ML^3T^{-3}I^{-1}].$$

Its SI unit is $\text{N m}^2 \text{C}^{-1}$. The sign of flux is fixed by the chosen surface normal.

Step 3: Conclusion Electric flux is the surface integral $\Phi_E = \int_S \vec{E} \cdot d\vec{A}$, with dimensions $[ML^3T^{-3}I^{-1}]$ and SI unit $\text{N m}^2 \text{C}^{-1}$.

Quick Tip to Solve: Write flux as field times area, then replace field by force per charge and charge by current times time to obtain its dimensions.

23(b). A plane surface, in shape of a square of side 1 cm is placed in an electric field $\vec{E} = \left(100 \frac{\text{N}}{\text{C}}\right) \hat{i}$ such that the unit vector normal to the surface is given by $\hat{n} = 0.8\hat{i} + 0.6\hat{k}$. Find the electric flux through the surface.

Solution:

Concept:

- Electric flux through a surface measures the electric field passing normally through that surface: $\Phi_E = \int_S \vec{E} \cdot d\vec{A}$, where $d\vec{A} = \hat{n} dA$ is the oriented area element.
- For a uniform electric field and a plane surface, $\Phi_E = \vec{E} \cdot \vec{A} = EA \cos \theta$, where θ is the angle between the field and the surface normal.

Step 1: Convert the side length and form the area vector The side of the square is $1 \text{ cm} = 10^{-2} \text{ m}$, so its area, after squaring the conversion factor, is

$$A = (10^{-2})^2 = 10^{-4} \text{ m}^2.$$

The given normal is a unit vector because $0.8^2 + 0.6^2 = 1$. Thus

$$\vec{A} = 10^{-4}(0.8\hat{i} + 0.6\hat{k}) \text{ m}^2.$$

Step 2: Evaluate the scalar product Only the area component parallel to the electric field contributes. Using $\hat{i} \cdot \hat{i} = 1$ and $\hat{i} \cdot \hat{k} = 0$,

$$\Phi_E = (100)(10^{-4})(0.8) = 8.0 \times 10^{-3} \text{ N m}^2 \text{ C}^{-1}.$$

The positive sign shows that the field has a component along the specified normal.

Step 3: Conclusion The electric flux through the specified square is $+8.0 \times 10^{-3} \text{ N m}^2 \text{ C}^{-1}$, positive relative to the given normal.

Quick Tip to Solve: Square the centimetre-to-metre conversion when finding area; then use the normal's $\hat{i}$ coefficient directly because the field is along $\hat{i}$.

24(a)(i). State Lenz's Law. In a closed circuit, the induced current opposes the change in magnetic flux that produced it as per the law of conservation of energy. Justify. [3 marks total]

Solution:

Concept:

- Lenz's law gives the direction of induction: the induced current produces a magnetic field that opposes the change in magnetic flux responsible for that current.
- Faraday's law for one loop is $\varepsilon = -d\Phi_B/dt$. The minus sign represents opposition to the change of magnetic flux Φ_B .

Step 1: State Lenz's law Lenz's law states that the induced current flows in such a direction that its magnetic effect opposes the change in magnetic flux that produces it. This opposition is represented by the minus sign in Faraday's law, $\varepsilon = -d\Phi_B/dt$ for a single loop.

Step 2: Relate the opposing effect to energy conservation When a magnet approaches a conducting loop, the induced current makes the nearer face repel it. External work is needed to continue the

approach; this work supplies the electrical energy dissipated as heat. If induction aided the change, the magnet would accelerate while heat was generated without an external energy supply, violating conservation of energy. Thus the induced effect must oppose the flux change.

Step 3: Conclusion The induced current opposes the change in flux that produces it. Mechanical work done against this opposition supplies the induced electrical energy, so the direction given by Lenz's law obeys conservation of energy.

Quick Tip to Solve: For a magnet approaching a loop, imagine the nearer face repelling it; work against that repulsion supplies the electrical energy.

24(a)(ii). A metal rod of length 2 m is rotated with a frequency 60 rev/s about an axis passing through its centre and perpendicular to its length. A uniform magnetic field of 2 T perpendicular to its plane of rotation is switched-on in the region. Calculate the e.m.f. induced between the centre and the end of the rod.

Solution:

Concept:

- The centre-to-end distance of a rod of total length L is $R = L/2$; its angular speed is $\omega = 2\pi f$, where f is the rotation frequency.
- In a rod rotating in a uniform perpendicular magnetic field, an element at distance r from the axis has speed $v = \omega r$ and contributes motional emf $d\varepsilon = B\omega r dr$.

Step 1: Identify the rotating radius and angular speed The axis passes through the centre of the 2 m rod. The distance from the centre to one end is consequently $R = 1$ m, not the full rod length. For rotation frequency $f = 60$ rev/s,

$$\omega = 2\pi f = 120\pi \text{ rad s}^{-1}.$$

The magnetic field magnitude is $B = 2$ T.

Step 2: Integrate the motional emf from the centre to the end The force per unit charge has magnitude $vB = B\omega r$ and acts along the rotating rod. The magnitude of the centre-to-end emf is therefore

$$\varepsilon = \int_0^R B\omega r dr = \frac{1}{2}B\omega R^2.$$

Substitution gives

$$\varepsilon = \frac{1}{2}(2)(120\pi)(1)^2 = 120\pi \text{ V} \simeq 377 \text{ V}.$$

The sense of rotation relative to the field determines the polarity; neither sense is specified, so the requested result is the magnitude.

Step 3: Conclusion The magnitude of the emf between the centre and either end is $120\pi \text{ V} \approx 377 \text{ V}$. Its polarity depends on the unspecified sense of rotation and direction of the magnetic field.

Quick Tip to Solve: For centre-to-end emf, use half the rod length as R in $\varepsilon = B\omega R^2/2$; the total rod length would overestimate this emf fourfold.

24(b)(i). State and explain Ampere's circuital law.

[3 marks total]

Solution:**Concept:**

- Ampere's circuital law for steady currents is $\oint_C \vec{B} \cdot d\vec{l} = \mu_0 I_{\text{enc}}$, where I_{enc} is the algebraic current threading the surface bounded by the closed path C .
- The scalar product $\vec{B} \cdot d\vec{l}$ selects the tangential magnetic-field component along each small element of the closed integration path.

Step 1: State Ampere's circuital law The line integral of the magnetic field around a closed path equals μ_0 times the net steady current passing through the surface bounded by that path:

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

Step 2: Explain the terms and sign convention Here $d\vec{l}$ is a directed path element and μ_0 is the permeability of free space. Only the component of $\vec{B}$ along the path contributes to the integral. The right-hand rule relates the direction of traversal to the positive normal of the surface; currents along that normal count positive and opposite currents count negative. For a circular path around a long straight wire, symmetry gives $B(2\pi r) = \mu_0 I$.

Step 3: Conclusion For steady currents, $\oint_C \vec{B} \cdot d\vec{l} = \mu_0 I_{\text{enc}}$. The enclosed current is an algebraic sum, with its positive direction linked to traversal of the loop by the right-hand rule.

Quick Tip to Solve: Choose a path with constant tangential field when symmetry allows; the integral then becomes field strength times path length.

24(b)(ii). Two long straight parallel wires separated by 20 cm, carry 5 A and 10 A current respectively, in the same direction. Find the magnitude and direction of the net magnetic field at a point midway between them.

Solution:**Concept:**

- A long straight wire carrying current I produces field $B = \mu_0 I / (2\pi r)$ at perpendicular distance r . Its direction follows the right-hand thumb rule.
- Magnetic fields obey vector superposition: $\vec{B}_{\text{net}} = \vec{B}_1 + \vec{B}_2$. Between parallel wires carrying currents in the same direction, their fields oppose one another.

Step 1: Calculate the field due to each wire The midpoint is $r = (20 \text{ cm})/2 = 0.10 \text{ m}$ from either wire. Taking $\mu_0 = 4\pi \times 10^{-7} \text{ T m A}^{-1}$,

$$B_5 = \frac{\mu_0(5)}{2\pi(0.10)} = 1.0 \times 10^{-5} \text{ T},$$

$$B_{10} = \frac{\mu_0(10)}{2\pi(0.10)} = 2.0 \times 10^{-5} \text{ T}.$$

The equal distances make the field strengths proportional to the currents.

Step 2: Apply the right-hand rule and superpose the fields Because the currents flow in the same direction, their magnetic fields at a point between the wires are opposite. Hence the net magnitude is the difference,

$$B_{\text{net}} = B_{10} - B_5 = 1.0 \times 10^{-5} \text{ T}.$$

The net field is perpendicular to the plane containing the two wires and points in the direction of the field due to the 10 A wire. For example, draw both currents upward, with the 5 A wire on the left and the 10 A wire on the right. At the midpoint, the stronger field is out of the page, so the net field is out of the page in that chosen orientation.

Step 3: Conclusion At the midpoint, $B_{\text{net}} = 1.0 \times 10^{-5} \text{ T}$, perpendicular to the plane of the wires and in the direction of the field due to the 10 A wire.

Quick Tip to Solve: Between two parallel wires with currents in the same direction, subtract their fields; at the midpoint the stronger current decides the net direction.

25. An electron moving with a velocity $\vec{v} = (1.0 \times 10^7 \text{ m/s})\hat{i} + (0.5 \times 10^7 \text{ m/s})\hat{j}$ enters a region of uniform magnetic field $\vec{B} = (0.5 \text{ mT})\hat{j}$. Find the radius of the circular path described by it. While rotating; does the electron trace a linear path too? If so, calculate the linear distance covered by it during the period of one revolution. [3 marks]

Solution:

Concept:

- In a uniform magnetic field, the perpendicular velocity produces circular motion: $r = mv_{\perp}/(|q|B)$. Here m is the particle mass and $|q|$ its charge magnitude.
- The parallel velocity remains constant because $\vec{F} = q\vec{v} \times \vec{B}$ has no component along the field. The period is $T = 2\pi m/(|q|B)$ and the helical pitch is $p = v_{\parallel}T$.

Step 1: Resolve the velocity relative to the field The magnetic field is along $+\hat{j}$. Therefore the $\hat{i}$ component is perpendicular to the field, whereas the $\hat{j}$ component is parallel to it:

$$v_{\perp} = 1.0 \times 10^7 \text{ m s}^{-1}, \quad v_{\parallel} = 0.5 \times 10^7 \text{ m s}^{-1}.$$

Convert the field before substituting: $B = 0.5 \text{ mT} = 5.0 \times 10^{-4} \text{ T}$. Only the perpendicular component, not the total speed, determines the radius.

Step 2: Equate magnetic force to centripetal force Taking $m_e = 9.1 \times 10^{-31} \text{ kg}$ and $e = 1.6 \times 10^{-19} \text{ C}$,

$$ev_{\perp}B = \frac{m_e v_{\perp}^2}{r}, \quad r = \frac{(9.1 \times 10^{-31})(1.0 \times 10^7)}{(1.6 \times 10^{-19})(5.0 \times 10^{-4})} = 0.11375 \text{ m}.$$

The electron's negative charge reverses the sense of rotation; the radius depends on the positive magnitude of its charge.

Step 3: Find the axial advance in one revolution The unchanged $v_{\parallel}$ carries the electron uniformly along $+\hat{j}$ while it rotates in a plane perpendicular to the field. Thus its actual three-dimensional trajectory is a helix.

$$T = \frac{2\pi m_e}{eB} = \frac{2\pi(9.1 \times 10^{-31})}{(1.6 \times 10^{-19})(5.0 \times 10^{-4})} = 7.15 \times 10^{-8} \text{ s}.$$

$$p = v_{\parallel} T = (0.5 \times 10^7)(7.15 \times 10^{-8}) = 0.357 \text{ m.}$$

This distance is the linear advance along the field during one turn, not the length measured along the curved helical track.

Step 4: Conclusion The radius is $r \approx 0.114 \text{ m}$. Yes, a uniform linear motion along the magnetic field accompanies the rotation; the distance advanced in one revolution is $p \approx 0.357 \text{ m}$ along $+\hat{j}$.

Quick Tip to Solve: Use only the velocity perpendicular to $\vec{B}$ for radius, and multiply the parallel velocity by the period to obtain pitch.

Name the parts of the electromagnetic spectrum which are

26(a)(i). also known as ‘heat waves’.

[3 marks total]

Solution:

Concept:

- Infrared radiation lies beyond the red end of visible light. Matter absorbs it readily and converts its energy into thermal energy, so it is commonly called heat radiation.
- Absorption transfers electromagnetic energy to matter; this can raise the temperature even when the incident radiation is invisible.

Step 1: Locate the relevant spectral region Infrared rays lie immediately beyond the red end of the visible spectrum and have wavelengths longer than visible red light. Hot bodies, such as a heater element, emit this radiation.

Step 2: Connect the name with the heating effect When absorbed by matter, infrared radiation increases molecular motion and internal energy. The consequent temperature rise explains the familiar name heat waves. Other electromagnetic radiation can also heat matter when absorbed, but this question asks for the conventional name of a spectral region.

Step 3: Conclusion The waves conventionally called heat waves are infrared rays.

Quick Tip to Solve: Associate a heater and an invisible thermal signal with infrared, the region just beyond visible red.

26(a)(ii). absorbed by ozone layer in the atmosphere.

Solution:

Concept:

- Ultraviolet radiation lies beyond the violet end of visible light. Atmospheric ozone strongly absorbs harmful ultraviolet radiation and protects life at Earth’s surface.
- Ultraviolet wavelengths are shorter than visible violet wavelengths; absorbing this energetic solar radiation reduces its intensity reaching the ground.

Step 1: Identify the radiation screened by ozone The ozone layer absorbs a substantial amount of harmful solar ultraviolet radiation. It thereby reduces the exposure of living organisms at Earth’s surface to this radiation.

Step 2: Distinguish the named region from infrared The question asks for the electromagnetic spectral

region absorbed by atmospheric ozone. Its expected identification is ultraviolet; infrared is the region associated with the separate heat-waves description. Ozone does not absorb all wavelengths equally, and the statement need not imply complete removal of every ultraviolet wavelength.

Step 3: Conclusion The requested part of the electromagnetic spectrum is ultraviolet radiation.

Quick Tip to Solve: Link atmospheric ozone protection to ultraviolet radiation; keep it distinct from infrared heat radiation.

26(b). Write briefly one method each, of the production and detection of these radiations.

Solution:

Concept:

- Infrared radiation lies beyond the red end of visible light. Matter absorbs it readily and converts its energy into thermal energy, so it is commonly called heat radiation.
- Ultraviolet radiation lies beyond the violet end of visible light. Atmospheric ozone strongly absorbs harmful ultraviolet radiation and protects life at Earth's surface.

Step 1: State one infrared source and detector **Production:** Heat a body, for example an electric heater element. Thermal motion and molecular vibrations in the hot material produce infrared radiation.

Detection: Use a thermopile. Infrared radiation incident on its blackened junctions raises their temperature relative to the reference junctions. The resulting thermoelectric emf indicates the presence of the radiation. This detector uses the heating effect that gives infrared its familiar name.

Step 2: State one ultraviolet source and detector **Production:** Pass an electric discharge through mercury vapour in a quartz mercury-vapour lamp. Excited mercury atoms emit ultraviolet radiation; quartz allows this radiation to emerge from the lamp.

Detection: Use a fluorescent screen. The screen absorbs ultraviolet photons and emits visible light, so the otherwise invisible ultraviolet radiation is detected by the visible fluorescence. The screen is a detector, while the mercury discharge is the source.

Step 3: Conclusion Infrared: a hot body produces it and a thermopile detects it. Ultraviolet: a mercury-vapour discharge produces it and a fluorescent screen detects it.

Quick Tip to Solve: Pair infrared with a thermal detector and ultraviolet with a fluorescent screen; give both a source and a detector for each region.

27(a). Explain the characteristics of a p-n junction diode that makes it suitable for its use as a rectifier. [3 marks total]

Solution:

Concept:

- A p-n junction diode offers low resistance in forward bias and very high resistance in reverse bias, below breakdown. It therefore allows appreciable current mainly in one direction.
- Rectification converts alternating input into unidirectional current by exploiting the asymmetry of the diode's current-voltage characteristic.

Step 1: Explain the forward-bias characteristic In forward bias, the p side is connected to the positive supply terminal and the n side to the negative terminal. The junction potential barrier and depletion width decrease. A substantial current then flows when the applied voltage sufficiently overcomes the barrier, giving the diode a low effective forward resistance.

Step 2: Explain reverse bias and connect it to rectification In reverse bias, the junction barrier and depletion width increase. Majority carriers are blocked and only a small minority-carrier leakage current flows below breakdown, so the reverse resistance is very high. During an AC input the diode therefore conducts appreciably in the forward direction and suppresses current in the opposite direction. This one-way behaviour provides rectification; operation is kept below reverse breakdown.

Step 3: Conclusion The strongly asymmetric current-voltage characteristic, with low forward resistance and very high reverse resistance below breakdown, makes a p-n junction diode suitable for producing unidirectional current from AC.

Quick Tip to Solve: Explain both bias conditions: forward bias lowers the barrier and conducts, whereas reverse bias raises the barrier and nearly blocks current.

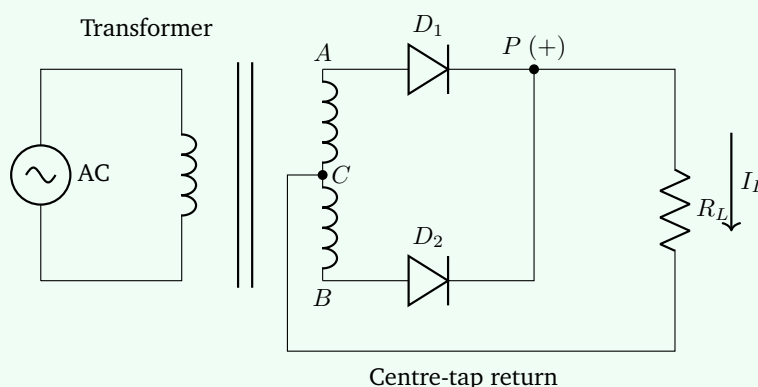
27(b). With the help of a circuit diagram, explain the working of a full wave rectifier.

Solution:

Concept:

- A p-n junction diode offers low resistance in forward bias and very high resistance in reverse bias, below breakdown. It therefore allows appreciable current mainly in one direction.
- A centre-tapped full-wave rectifier uses two diodes on alternate half-cycles so that current through the load R_L has the same direction during both halves of the AC input.

Step 1: Connect the full-wave rectifier Connect the ends A and B of a centre-tapped transformer secondary to the anodes of D_1 and D_2 . Join their cathodes at P , the positive output terminal, and connect R_L between P and the centre tap C . The voltages at A and B , measured relative to C , are opposite in phase. The circuit below shows both diode cathodes on the right.



Centre-tapped full-wave rectifier; load current flows downward in both half-cycles.

Step 2: Follow the two half-cycles During the half-cycle when A is positive relative to C , B is negative. Diode D_1 conducts and D_2 is reverse biased. Conventional current follows $A \rightarrow D_1 \rightarrow P \rightarrow R_L \rightarrow C$, returning through the upper half of the secondary.

During the next half-cycle, B becomes positive and A negative relative to C . Now D_2 conducts and D_1 blocks. Current follows $B \rightarrow D_2 \rightarrow P \rightarrow R_L \rightarrow C$, returning through the lower half of the secondary.

Hence both input half-cycles produce load current from P towards C . The output is pulsating DC; without a smoothing filter it is not constant DC. If the input frequency is f , the output pulse frequency is $2f$.

Step 3: Conclusion The two diodes conduct alternately, giving current through R_L from P to C during both AC half-cycles. The resulting pulsating DC has pulse frequency $2f$.

Quick Tip to Solve: Trace each conducting loop back to the centre tap: both diode cathodes meet at the positive output, so the load-current direction stays the same.

Explain the following, giving reasons:

28(a). A doped semiconductor is electrically neutral.

[3 marks total]

Solution:

Concept:

- Doping introduces neutral impurity atoms into a neutral semiconductor crystal; it does not add net electric charge.
- Ionisation transfers charge between impurity atoms and mobile carriers. The total positive and negative charges remain equal.

Step 1: Account for donor doping In an n-type semiconductor, a donor atom releases an electron for conduction and becomes an immobile positive donor ion. The electron's negative charge is exactly balanced by the donor ion's positive charge.

Step 2: Account for acceptor doping In a p-type semiconductor, an acceptor atom accepts a valence electron and becomes an immobile negative acceptor ion. The hole left in the valence band has an equal positive charge. Thus increasing the number of mobile carriers does not create a net charge in the crystal.

Step 3: Conclusion A doped semiconductor is electrically neutral because the charge of its mobile carriers is balanced by the opposite charge of its ionised impurity atoms.

Quick Tip to Solve: When checking neutrality, count the fixed impurity ions as well as the mobile electrons or holes.

28(b). In a p-n junction under equilibrium, there is no net current.

Solution:

Concept:

- Diffusion current results from the concentration gradient of carriers across a p-n junction.
- The electric field of the depletion region produces a drift current opposite to the diffusion current.

Step 1: Identify the diffusion current Electrons tend to diffuse from the n-side to the p-side, while holes tend to diffuse from the p-side to the n-side. Both contributions give a conventional diffusion current from the p-side towards the n-side.

Step 2: Apply the equilibrium condition The exposed fixed ions form a depletion-region field directed from the n-side to the p-side. This field produces an opposing drift current. At thermal equilibrium,

the barrier adjusts until these two currents have equal magnitudes:

$$I_{\text{diff}} + I_{\text{drift}} = 0,$$

where the currents are signed along the same reference direction. Individual carrier motions still occur.

Step 3: Conclusion There is no net current at equilibrium because the diffusion and drift currents are equal in magnitude and opposite in direction.

Quick Tip to Solve: Explain zero net current by balancing drift and diffusion; do not assume that all carriers stop moving.

28(c). In a diode, the reverse current is practically not dependent on the applied voltage.

Solution:

Concept:

- The reverse current in a p-n junction is due mainly to thermally generated minority carriers: electrons in the p-region and holes in the n-region.
- At fixed temperature and below reverse breakdown, this current is approximately the reverse saturation current.

Step 1: Identify the carrier supply Reverse bias suppresses the flow of majority carriers. The junction field sweeps minority carriers reaching the depletion region across the junction. Their supply is controlled mainly by thermal generation, and therefore by temperature.

Step 2: Increase the reverse bias A larger reverse voltage strengthens the field, but nearly all available minority carriers are already collected. Their rate of supply changes little, so increasing the voltage does not appreciably increase the current. This statement applies in the ordinary reverse-bias region, before breakdown; breakdown causes a sharp current increase.

Step 3: Conclusion At constant temperature and below breakdown, reverse current is practically independent of the applied reverse voltage because it is limited by the supply of thermally generated minority carriers.

Quick Tip to Solve: For reverse current, track minority-carrier generation and temperature; check that breakdown has not begun.

Section D (8 marks)

29. Dielectrics play an important role in design of capacitors. The molecules of a dielectric may be polar or non-polar. When a dielectric slab is placed in an external electric field, opposite charges appear on the two surfaces of the slab perpendicular to electric field. Due to this an electric field is established inside the dielectric. The capacitance of a capacitor is determined by the dielectric constant of the material that fills the space between the plates. Consequently, the energy storage capacity of a capacitor is also affected. Like resistors, capacitors can also be arranged in series and/or parallel. [4 marks]

29(i). Which of the following is a polar molecule? [1 mark]

- (A) O_2
- (B) H_2
- (C) N_2
- (D) HCl

Correct Answer: (D) HCl

Solution:

Concept:

- A polar molecule has a permanent electric dipole moment because its centres of positive and negative charge do not coincide.
- Identical atoms in a homonuclear diatomic molecule share bonding electrons symmetrically; unequal electron sharing in a heteronuclear diatomic molecule can produce a permanent dipole.

Step 1: Examine the identical-atom molecules In O_2 , H_2 and N_2 , the two atoms are identical. Their charge distribution is symmetric, so each has zero permanent dipole moment. They may develop induced dipoles in an external field, but that does not make them polar molecules.

Step 2: Examine the hydrogen chloride molecule Chlorine attracts the shared electron pair more strongly than hydrogen. The chlorine end has a partial negative charge and the hydrogen end a partial positive charge. These separated charge centres give HCl a nonzero permanent dipole moment, even without an applied field.

Step 3: Conclusion HCl is the polar molecule. Hence, the correct option is (D).

Quick Tip to Solve: For these diatomic choices, eliminate the three identical-atom molecules: they have no permanent dipole.

29(ii). Which of the following statements about dielectrics is correct?

[1 mark]

- (A) A polar dielectric has a net dipole moment in absence of an external electric field which gets modified due to the induced dipoles.
- (B) The net dipole moments of induced dipoles is along the direction of the applied electric field.
- (C) Dielectrics contain free charges.
- (D) The electric field produced due to induced surface charges inside a dielectric is along the external electric field.

Correct Answer: (B) The net dipole moments of induced dipoles is along the direction of the applied electric field.

Solution:

Concept:

- The electric dipole moment points from negative to positive charge. An external electric field induces a net dipole moment along itself.
- In an ordinary polar dielectric without an applied field, random molecular orientations give zero macroscopic net dipole moment despite permanent molecular dipoles.

Step 1: Determine the direction of the induced dipole moment An applied field displaces positive bound charge slightly along the field and negative bound charge oppositely. The induced dipole moment, directed from the negative to the positive charge centre, therefore lies along the applied field. This is the statement in option (B).

Step 2: Check the other statements Option (A) confuses the permanent dipole moment of an individual polar molecule with the net dipole moment of the whole unpolarised dielectric: randomly directed molecular moments cancel. Option (C) is false in the ideal dielectric model because charges are bound, rather than free to flow as in a conductor. Option (D) reverses the depolarising field: the induced surface charges create an internal field opposite to the applied field and reduce the resultant field.

Step 3: Conclusion The net dipole moment of the induced dipoles is along the applied electric field. Hence, the correct option is (B).

Quick Tip to Solve: Distinguish the two directions: induced dipole moment is along the applied field, but the field of the induced surface charges opposes it.

29(iii). When a dielectric slab is inserted between the plates of an isolated charged capacitor, the energy stored in it:

[1 mark]

- (A) increases and the electric field inside it also increases.
- (B) decreases and the electric field also decreases.
- (C) decreases and the electric field increases.
- (D) increases and the electric field decreases.

Correct Answer: (B) decreases and the electric field also decreases.

Solution:

Concept:

- An isolated charged capacitor cannot exchange charge with a battery, so its free plate charge Q remains constant.

- Stored energy is $U = Q^2/(2C)$, where C is capacitance. A dielectric increases capacitance and its polarisation opposes the field of the free charges.

Step 1: Compare the stored energies at fixed charge Inserting a dielectric increases the capacitance. Since the capacitor is isolated, the relevant expression is $U = Q^2/(2C)$ at constant Q . Thus the stored energy decreases. If the dielectric fills the gap completely, $C' = KC$ and $U' = U/K$, where the dielectric constant $K > 1$.

Step 2: Compare the electric fields Bound charges appear on the dielectric surfaces. Their field opposes the field of the unchanged free plate charges, so the resultant field inside the dielectric decreases. For complete filling, $E' = E/K$. Equivalently, the potential difference falls as $V' = Q/C'$. Options (A) and (D) wrongly predict an energy increase, while option (C) wrongly predicts an electric-field increase.

Step 3: Conclusion Both stored energy and the electric field decrease. Hence, the correct option is (B).

Quick Tip to Solve: Underline “isolated”: hold charge fixed and use $Q^2/(2C)$, so an increase in capacitance lowers the energy.

29(iv)(a). An air-filled capacitor with plate area A and plate separation d has capacitance C_0 . A slab of dielectric constant K , area A and thickness $\left(\frac{d}{5}\right)$ is inserted between the plates. The capacitance of the capacitor will become: [1 mark]

- (A) $\left[\frac{4K}{5K+1}\right] C_0$
 (B) $\left[\frac{K+5}{4}\right] C_0$
 (C) $\left[\frac{5K}{4K+1}\right] C_0$
 (D) $\left[\frac{K+4}{5K}\right] C_0$

Correct Answer: (C) $\left[\frac{5K}{4K+1}\right] C_0$

Solution:

Concept:

- The original air capacitance is $C_0 = \epsilon_0 A/d$, where A is plate area and d the separation.
- Air and dielectric layers stacked along the electric field act as capacitors in series. A dielectric thickness t contributes an effective air thickness t/K .

Step 1: Find the effective plate separation The slab covers the entire plate area but occupies only $t = d/5$ of the gap. The remaining air thickness is $4d/5$. The potential differences across these successive regions add; consequently,

$$d_{\text{eff}} = (d - t) + \frac{t}{K} = \frac{4d}{5} + \frac{d}{5K} = \frac{d(4K + 1)}{5K}.$$

Step 2: Express the new capacitance in terms of the original Replace the actual layered gap by its

effective air thickness:

$$C = \frac{\epsilon_0 A}{d_{\text{eff}}} = \frac{\epsilon_0 A}{d} \frac{5K}{4K+1} = \frac{5K}{4K+1} C_0.$$

Only option (C) agrees with the series-layer expression. As checks, $K = 1$ gives $C = C_0$, while very large K gives $C \rightarrow 5C_0/4$; the remaining air gap prevents an unlimited increase. Options (A), (B) and (D) fail these limits or the derived expression.

Step 3: Conclusion The capacitance becomes $C = \frac{5K}{4K+1} C_0$. Hence, the correct option is (C).

Quick Tip to Solve: For a full-area slab, replace its thickness by t/K ; keep the remaining air thickness unchanged before calculating capacitance.

OR

29(iv)(b). Two capacitors of capacitances $2C_0$ and $6C_0$ are first connected in series and then in parallel across the same battery. The ratio of energies stored in series combination to that in parallel is: [1 mark]

- (A) $\frac{1}{4}$
- (B) $\frac{1}{6}$
- (C) $\frac{2}{15}$
- (D) $\frac{3}{16}$

Correct Answer: (D) $\frac{3}{16}$

Solution:

Concept:

- The energy stored across a battery of potential difference V is $U = \frac{1}{2} C_{\text{eq}} V^2$, where C_{eq} is the equivalent capacitance.
- For two capacitors, $C_s = C_1 C_2 / (C_1 + C_2)$ in series and $C_p = C_1 + C_2$ in parallel.

Step 1: Calculate the equivalent capacitances With $C_1 = 2C_0$ and $C_2 = 6C_0$, the two connections give

$$C_s = \frac{(2C_0)(6C_0)}{2C_0 + 6C_0} = \frac{3}{2} C_0,$$
$$C_p = 2C_0 + 6C_0 = 8C_0.$$

The series capacitance is less than either individual capacitance; the parallel capacitance is their sum.

Step 2: Form the energy ratio for the same battery The same voltage V is applied across the complete combination in each case. Therefore the common factor $V^2/2$ cancels:

$$\frac{U_s}{U_p} = \frac{C_s}{C_p} = \frac{(3/2)C_0}{8C_0} = \frac{3}{16}.$$

The individual series capacitors do not each receive the full battery voltage, so their energies cannot be calculated by assigning V to both. Options (A), (B) and (C) do not equal the ratio of the equivalent capacitances.

Step 3: Conclusion The ratio of energy stored in series to that in parallel is $\frac{3}{16}$. Hence, the correct option is (D).

Quick Tip to Solve: With the same battery, the energy ratio equals the equivalent-capacitance ratio; calculate the combinations before using the energy formula.

30. A prism is an optical medium bounded by three refracting plane surfaces. A ray of light suffers successive refractions on passing through its two surfaces and deviates by a certain angle from its original path. The refractive index of the material of the prism is given by $\mu = \sin\left(\frac{A + \delta_m}{2}\right) / \sin \frac{A}{2}$. If the angle of incidence on the second surface is greater than an angle called critical angle, the ray will not be refracted from the second surface and is totally internally reflected. [4 marks]

30(i). The critical angle for glass is θ_1 and that for water is θ_2 . The critical angle for glass-water surface would be (given ${}_a\mu_g = 1.5$, ${}_a\mu_w = 1.33$): [1 mark]

- (A) less than θ_2
- (B) between θ_1 and θ_2
- (C) greater than θ_2
- (D) less than θ_1

Correct Answer: (C) greater than θ_2

Solution:

Concept:

- For light going from refractive index n_1 to a smaller index n_2 , the critical angle C satisfies $\sin C = n_2/n_1$.
- The stated critical angles for glass and water refer to their interfaces with air, whose refractive index is approximately unity.

Step 1: Evaluate the air-interface critical angles The given indices yield $\sin \theta_1 = 1/1.5 = 0.667$ and $\sin \theta_2 = 1/1.33 = 0.752$. Hence $\theta_1 \approx 41.8^\circ$ and $\theta_2 \approx 48.8^\circ$, so the water-air critical angle is larger.

Step 2: Compare the glass-water interface Light must travel from glass into water for a critical angle to exist. At this boundary,

$$\sin C = \frac{1.33}{1.5} = 0.887, \quad C \approx 62.5^\circ.$$

Sine increases between 0° and 90° , so C exceeds both air-interface angles. Options (A), (B) and (D) all place it below θ_2 and are excluded.

Step 3: Conclusion The glass-water critical angle is greater than θ_2 . Hence, the correct option is (C).

Quick Tip to Solve: Always use the receiving medium's index in the numerator of $\sin C = n_2/n_1$.

30(ii). When a ray of light of wavelength λ and frequency ν is refracted into a denser medium:

[1 mark]

- (A) λ and ν both increase.
- (B) λ increases but ν is unchanged.
- (C) λ decreases but ν is unchanged.
- (D) λ and ν both decrease.

Correct Answer: (C) λ decreases but ν is unchanged.

Solution:

Concept:

- Wave speed, frequency and wavelength obey $v = \nu\lambda$, where v is the speed in the medium.
- Frequency is fixed by the source and remains continuous at a stationary boundary. Optical density is measured by refractive index $n = c/v$.

Step 1: Determine the changes in speed and frequency A denser optical medium has a larger refractive index, so light travels more slowly in it. Refraction does not change the source's oscillation rate: the incoming and transmitted waves have the same frequency ν . Thus neither an increase nor a decrease of frequency occurs.

Step 2: Use the wave relation Since $\lambda = v/\nu$, the smaller speed with unchanged frequency produces a smaller wavelength. Equivalently, $\lambda_2/\lambda_1 = n_1/n_2 < 1$. Options (A) and (D) incorrectly change frequency; option (B) preserves frequency but incorrectly increases wavelength.

Step 3: Conclusion The wavelength decreases while the frequency remains unchanged. Hence, the correct option is (C).

Quick Tip to Solve: At a stationary refracting boundary, keep frequency fixed and let wavelength change with speed.

30(iii)(a). The critical angle for a ray of light passing from glass to water is minimum for:

[1 mark]

- (A) red colour
- (B) blue colour
- (C) yellow colour
- (D) violet colour

Correct Answer: (D) violet colour

Solution:

Concept:

- At a glass-water boundary the critical angle C satisfies $\sin C = n_w/n_g = 1/\mu_{gw}$, where $\mu_{gw} = n_g/n_w$ is the relative index of glass with respect to water.
- In the usual visible-light dispersion model for glass relative to water, violet has the largest relative refractive index and red the smallest.

Step 1: Relate critical angle to relative index At critical incidence, the refracted ray makes 90° with the normal. Snell's law therefore gives $n_g \sin C = n_w$. Since sine increases throughout the possible range of critical angles, the smallest critical angle corresponds to the largest relative index n_g/n_w .

Step 2: Compare the listed colours For ordinary dispersion, the relative index increases in the order

red, yellow, blue, violet. Consequently the critical angles have the reverse order:

$$C_V < C_B < C_Y < C_R.$$

Blue has a smaller critical angle than yellow or red, but violet has the smallest of all four. Thus options (A), (B) and (C) cannot supply the minimum.

Step 3: Conclusion The critical angle is minimum for violet light. Hence, the correct option is (D).

Quick Tip to Solve: Compare the relative index of the two media: the largest relative index gives the smallest critical angle.

OR

30(iii)(b). Three beams of red, yellow and violet colours are passed through a prism, one by one under the same condition. When the prism is in the position of minimum deviation, the angles of refraction from the second surface are r_R , r_Y and r_V respectively. Then: [1 mark]

(A) $r_V < r_Y < r_R$

(B) $r_Y < r_R < r_V$

(C) $r_R < r_Y < r_V$

(D) $r_R = r_Y = r_V$

Correct Answer: (C) $r_R < r_Y < r_V$

Solution:

Concept:

- At minimum deviation through a prism of angle A , the two internal refraction angles equal $A/2$, and the angle of emergence equals the angle of incidence.
- For refraction from the second face into air, Snell's law gives $\sin e = \mu \sin(A/2)$, with e the emergent angle and μ the prism's refractive index.

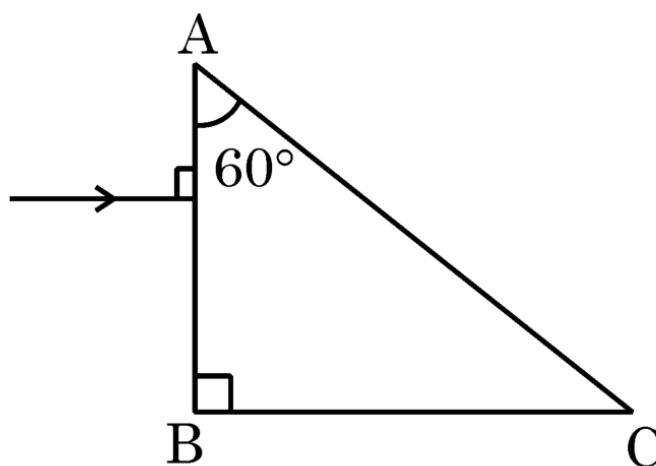
Step 1: Identify the angle requested at the second face The printed question asks for refraction from the second surface, so its symbols r_R, r_Y, r_V describe the outgoing refracted angles, that is, the angles of emergence. The equal internal angles $A/2$ are instead the angles of incidence at that second face. For each colour at its minimum-deviation position, Snell's law gives $\sin r_{\text{colour}} = \mu_{\text{colour}} \sin(A/2)$.

Step 2: Compare the indices for the three colours Ordinary dispersion in glass gives $\mu_R < \mu_Y < \mu_V$. The prism angle is fixed, and sine increases for emergent angles between 0° and 90° . Hence the emergent angles follow the same increasing order. Options (A) and (B) contradict this order; option (D) confuses the equal internal angles with the outgoing angles requested here.

Step 3: Conclusion The angles obey $r_R < r_Y < r_V$. Hence, the correct option is (C).

Quick Tip to Solve: At minimum deviation, internal angles equal $A/2$; outgoing angles still increase with refractive index.

30(iv). A ray of light is incident normally on a prism ABC of refractive index $\sqrt{2}$, as shown in figure. After it strikes face AC, it will: [1 mark]



- (A) go straight undeviated
- (B) just graze along the face AC
- (C) refract and go out of the prism
- (D) undergo total internal reflection

Correct Answer: (D) undergo total internal reflection

Solution:

Concept:

- A ray entering normally suffers no angular deviation. All incidence angles are measured from the normal to the relevant surface.
- At a prism-air interface, the critical angle satisfies $\sin C = 1/\mu$. Total internal reflection requires incidence from the denser side with $i > C$.

Step 1: Find the incidence angle on face AC The ray enters face AB normally, so it continues horizontally inside the prism, parallel to BC. The printed angles are $\angle A = 60^\circ$ and $\angle B = 90^\circ$; therefore $\angle C = 30^\circ$. The ray makes 30° with face AC and hence $i = 90^\circ - 30^\circ = 60^\circ$ with its normal.

Step 2: Compare incidence with the critical angle For the given refractive index,

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

Thus the ray strikes AC from inside the denser medium at $60^\circ > 45^\circ$. A grazing refracted ray would require equality, so (B) is excluded. Transmission as in (A) or (C) cannot occur above the critical angle.

Step 3: Conclusion The ray undergoes total internal reflection at face AC. Hence, the correct option is (D).

Quick Tip to Solve: In a prism, subtract the angle between ray and surface from 90° before comparing with the critical angle.

Section E (15 marks)

31(a)(i). Draw equipotential surfaces for an electric dipole.

[5 marks total]

Solution:

Concept:

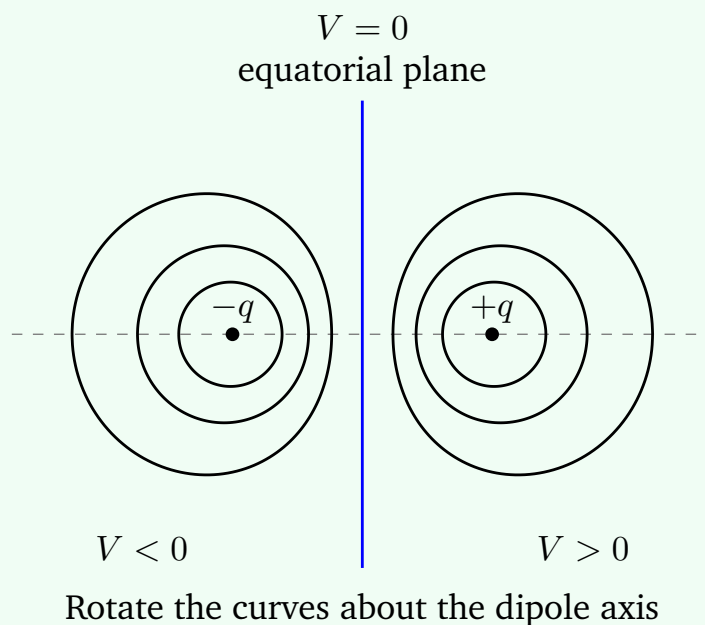
- An equipotential surface has constant electric potential. For charges $+q$ and $-q$, $V = kq(1/r_+ - 1/r_-)$, where r_+ and r_- are distances from the respective charges and $k = 1/(4\pi\epsilon_0)$.
- The electric field is normal to an equipotential surface because $\vec{E} = -\nabla V$; moving a charge along that surface requires zero electrostatic work.

Step 1: Identify the zero-potential plane For any point on the perpendicular bisector of the dipole axis, the two charge distances are equal. Thus

$$V = kq \left(\frac{1}{r_+} - \frac{1}{r_-} \right) = 0.$$

This perpendicular bisector becomes the equatorial plane in three dimensions. Its cross-section is the central vertical line in the drawing.

Step 2: Draw the positive and negative surfaces The curves below are cross-sections of equipotential surfaces in a plane containing the dipole axis. Rotating them about that axis gives the three-dimensional surfaces. Near each charge the surfaces are approximately spherical; farther away they are distorted by the other charge. Positive equipotentials surround $+q$, and negative equipotentials surround $-q$. The perpendicular bisector is the equatorial plane: here $r_+ = r_-$, so $V = 0$ everywhere. Electric field lines cross all equipotentials normally, and distinct equipotentials never intersect.



Cross-sections of dipole equipotential surfaces; the central vertical line represents the zero-potential plane.

Step 3: Conclusion The sketch shows nested positive equipotentials around $+q$, nested negative equipotentials around $-q$, and the zero-potential equatorial plane. Revolving the curves about the horizontal dipole axis gives the equipotential surfaces.

Quick Tip to Solve: Begin with the zero-potential perpendicular bisector, then draw mirrored nonintersecting contours around the two charges; equipotentials carry no directional arrows.

31(a)(ii). Two point charges q_1 and q_2 are located at $\vec{r}_1$ and $\vec{r}_2$ respectively in an external electric field $\vec{E}$. Obtain an expression for the potential energy of the system.

Solution:

Concept:

- Electrostatic potential energy equals the external work needed to assemble fixed charges quasi-statically. A charge q at external potential V_{ext} contributes qV_{ext} ; each distinct interacting pair is counted once.
- For separation $r_{12} = |\vec{r}_2 - \vec{r}_1|$, the mutual potential energy is kq_1q_2/r_{12} , where $k = 1/(4\pi\epsilon_0)$. The external potential excludes the fields of q_1 and q_2 .

Step 1: Bring the first charge into the external field Let $V_{\text{ext}}(\vec{r})$ denote the potential due to the sources of the given external field only. Keep those sources fixed. Using a common zero of external potential, bring q_1 to $\vec{r}_1$ before introducing q_2 . The external work is

$$W_1 = q_1 V_{\text{ext}}(\vec{r}_1).$$

The self-energies of the point charges and the unchanged energy of the external field sources are excluded. For a field whose potential is zero at infinity, this is work done in bringing the charge from infinity.

Step 2: Add the second charge and count the pair once Write $r_{12} = |\vec{r}_2 - \vec{r}_1|$. The potential at $\vec{r}_2$ now equals the external potential plus the potential of q_1 . Hence

$$W_2 = q_2 \left[V_{\text{ext}}(\vec{r}_2) + \frac{q_1}{4\pi\epsilon_0 r_{12}} \right].$$

Adding the two assembly works gives

$$U = q_1 V_{\text{ext}}(\vec{r}_1) + q_2 V_{\text{ext}}(\vec{r}_2) + \frac{q_1 q_2}{4\pi\epsilon_0 r_{12}}.$$

The first two terms describe the interactions with the external field; the last term is the mutual interaction. It must not be counted a second time. If the external field is uniform, choosing $V_{\text{ext}}(\vec{0}) = 0$ gives $V_{\text{ext}}(\vec{r}) = -\vec{E} \cdot \vec{r}$, so equivalently

$$U = -q_1 \vec{E} \cdot \vec{r}_1 - q_2 \vec{E} \cdot \vec{r}_2 + \frac{q_1 q_2}{4\pi\epsilon_0 r_{12}}.$$

Step 3: Conclusion With $r_{12} = |\vec{r}_2 - \vec{r}_1|$, the potential energy is

$$U = q_1 V_{\text{ext}}(\vec{r}_1) + q_2 V_{\text{ext}}(\vec{r}_2) + \frac{q_1 q_2}{4\pi\epsilon_0 r_{12}}.$$

It contains both interactions with the external field and one mutual interaction term.

Quick Tip to Solve: Write one external-potential term for each charge, then add the mutual interaction only once; using the total potential in both charge terms double-counts the pair.

31(a)(iii). The dipole moment of a molecule is 10^{-30} C m. It is placed in an electric field $\vec{E}$ of 10^5 V/m such that its axis is along the electric field. The direction of $\vec{E}$ is suddenly changed by 60° at an instant. Find the change in the potential energy of the dipole, at that instant.

Solution:

Concept:

- A dipole of moment $\vec{p}$ in a uniform field $\vec{E}$ has orientation energy $U = -\vec{p} \cdot \vec{E} = -pE \cos \theta$, where θ is the angle between them.
- A sudden change of field direction occurs before the molecule can rotate. Use its unchanged direction to find the new angle, and calculate $\Delta U = U_f - U_i$.

Step 1: Identify the initial and final angles Initially the dipole axis is along the electric field, so $\theta_i = 0^\circ$. At the instant the field direction changes by 60° , the molecule retains its original orientation. Thus the angle between $\vec{p}$ and the new field is $\theta_f = 60^\circ$. The field magnitude remains 10^5 V/m. This is the immediate change, before the dipole has time to turn under electric torque.

Step 2: Evaluate the energy difference Using $p = 10^{-30}$ C m, first obtain

$$pE = 10^{-30} \times 10^5 = 10^{-25} \text{ J}.$$

Hence

$$\begin{aligned} U_i &= -pE \cos 0^\circ = -10^{-25} \text{ J}, \\ U_f &= -pE \cos 60^\circ = -5.0 \times 10^{-26} \text{ J}, \\ \Delta U &= U_f - U_i = pE(1 - \cos 60^\circ) \\ &= +5.0 \times 10^{-26} \text{ J}. \end{aligned}$$

The energy becomes less negative because the dipole is less closely aligned with the field. The positive difference agrees with the fact that the aligned orientation has minimum energy.

Step 3: Conclusion The potential energy increases by $\Delta U = +5.0 \times 10^{-26} \text{ J}$ at that instant.

Quick Tip to Solve: For an initially aligned dipole and a sudden field turn through α , keep the dipole fixed and use $\Delta U = pE(1 - \cos \alpha)$.

A thin spherical shell of radius R has a uniform surface charge density σ . Using Gauss' law, deduce an expression for electric field

31(b)(i)(i). outside the shell.

[5 marks total]

Solution:

Concept:

- Gauss's law states $\oint \vec{E} \cdot d\vec{A} = Q_{\text{enc}}/\epsilon_0$, where Q_{enc} is the charge enclosed by a closed Gaussian surface.
- Spherical symmetry makes the field radial and its magnitude constant on a concentric sphere. The shell's total charge is $Q = 4\pi R^2\sigma$.

Step 1: Find the total charge and use symmetry The thin shell has radius R and uniform surface charge density σ , so its total charge is $Q = \sigma(4\pi R^2)$. Rotational symmetry about the centre permits no preferred tangential direction. Consequently the electric field is radial, with the same magnitude at every point of a concentric sphere. This symmetry allows the radial field component to be taken outside the flux integral.

Step 2: Choose a Gaussian surface outside the shell Take a concentric Gaussian sphere of radius $r > R$. The entire charge of the shell is enclosed. As the field is normal to the surface at every point, its outward radial component E_r satisfies

$$E_r(4\pi r^2) = \frac{4\pi R^2\sigma}{\epsilon_0}.$$

Therefore

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

Here $\hat{r}$ points radially outwards. The field is outward if $\sigma > 0$ and inward if $\sigma < 0$. Thus the exterior field is identical to that of the entire charge concentrated at the centre.

Step 3: Conclusion The exterior field is $\boxed{\vec{E} = \sigma R^2 \hat{r} / (\epsilon_0 r^2)}$ for $r > R$, outward for positive surface charge and inward for negative surface charge.

Quick Tip to Solve: Choose a concentric Gaussian sphere and use the shell radius R for charge, but the observation radius r for flux area.

31(b)(i)(ii). inside the shell.

Solution:

Concept:

- Gauss's law states $\oint \vec{E} \cdot d\vec{A} = Q_{\text{enc}}/\epsilon_0$, where Q_{enc} is the charge enclosed by a closed Gaussian surface.
- Spherical symmetry makes the field radial and its magnitude constant on a concentric sphere. The

shell's total charge is $Q = 4\pi R^2\sigma$.

Step 1: Establish the symmetry and enclosed charge For an observation point a distance $r < R$ from the centre, imagine a concentric spherical Gaussian surface through that point. The physical charge is confined to the shell at radius R , so none of it lies inside this smaller sphere. Uniform surface charge over the physical shell ensures spherical symmetry: the field can only be radial and its radial component has one common value on the Gaussian surface. This argument does not require the shell to be a conductor.

Step 2: Apply Gauss's law inside the shell Choose a concentric sphere with $0 < r < R$. All charge lies on the actual shell, outside this Gaussian surface, so $Q_{\text{enc}} = 0$. Spherical symmetry again makes the radial field constant on the Gaussian sphere. Hence

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

The centre also has zero field by symmetry. Zero enclosed charge alone would not imply zero field for an arbitrary distribution; the spherical symmetry is essential here. The limiting field just outside the shell is σ/ϵ_0 , while just inside it is zero.

Step 3: Conclusion The electric field everywhere inside the uniformly charged spherical shell is $\vec{E} = 0$, including its centre.

Quick Tip to Solve: Zero enclosed charge establishes zero flux; combine it with spherical symmetry to prove zero field for this shell.

31(b)(ii). Two long straight thin wires AB and CD have linear charge densities $10 \mu\text{C}/\text{m}$ and $-20 \mu\text{C}/\text{m}$, respectively. They are kept parallel to each other at a distance 1 m. Find magnitude and direction of the net electric field at a point midway between them.

Solution:

Concept:

- Gauss's law states $\oint \vec{E} \cdot d\vec{A} = Q_{\text{enc}}/\epsilon_0$, where Q_{enc} is the charge enclosed by a closed Gaussian surface.
- The field of a very long straight wire at perpendicular distance r is $E = |\lambda|/(2\pi\epsilon_0 r)$; it points away from positive charge and towards negative charge. Fields add vectorially.

Step 1: Determine the directions of the wire fields The midpoint is at a perpendicular distance $r = 0.50 \text{ m}$ from each wire. The field of positive wire AB points away from AB, towards CD. The field of negative wire CD points towards CD. Thus, at the midpoint, both fields point in the same direction along the common perpendicular, from AB to CD; their magnitudes must be added.

Step 2: Calculate and add the magnitudes Using $1/(4\pi\epsilon_0) = 9 \times 10^9 \text{ N m}^2\text{C}^{-2}$, the separate magnitudes are

$$E_{AB} = \frac{2(9 \times 10^9)(10 \times 10^{-6})}{0.50} = 3.6 \times 10^5 \text{ N C}^{-1},$$
$$E_{CD} = \frac{2(9 \times 10^9)(20 \times 10^{-6})}{0.50} = 7.2 \times 10^5 \text{ N C}^{-1}.$$

Therefore $E_{\text{net}} = E_{AB} + E_{CD} = 10.8 \times 10^5 \text{ N C}^{-1}$. The negative sign of CD's charge sets its field direction; it does not mean that its magnitude should be subtracted here.

Step 3: Conclusion The net field is $1.08 \times 10^6 \text{ N C}^{-1}$, perpendicular to the wires and directed from positive wire AB towards negative wire CD.

Quick Tip to Solve: At a midpoint between oppositely charged wires, mark both field arrows first: they point together, so add their magnitudes.

32(a)(i). You are given three circuit elements X, Y and Z. They are connected one by one across a given ac source. It is found that V and I are in phase for element X. V leads I by $\left(\frac{\pi}{4}\right)$ for element Y while I leads V by $\left(\frac{\pi}{4}\right)$ for element Z. Identify elements X, Y and Z. [5 marks total]

Solution:

Concept:

- In an ideal resistor, voltage and current are in phase. Inductive reactance makes voltage lead current; capacitive reactance makes current lead voltage. Ideal pure inductors and capacitors give phase differences of $\pi/2$.
- For series LCR, $X_L = \omega L$, $X_C = 1/(\omega C)$, and $\tan \phi = (X_L - X_C)/R$, with $\omega = 2\pi f$ and R the total series resistance.

Step 1: Identify the in-phase element For element X, voltage and current pass through corresponding zeroes and maxima together. Hence its impedance is real and its behaviour is resistive; the standard component identification is a resistor.

Step 2: Interpret the printed phase differences Element X is resistive. Element Y is inductive in nature and Z is capacitive in nature. However, the printed phase differences are $\pi/4$, not $\pi/2$: they do not describe an ideal pure inductor or an ideal pure capacitor. A simple consistent model is Y as a coil with series resistance R_Y , and Z as a capacitor with series resistance R_Z . At the given source frequency,

$$\tan \frac{\pi}{4} = \frac{X_L}{R_Y} = 1, \quad \tan \frac{\pi}{4} = \frac{X_C}{R_Z} = 1.$$

Thus $X_L = R_Y$ and $X_C = R_Z$ in this model. The phase data identify resistive, inductive and capacitive behaviour but do not uniquely specify the internal circuits. The usual identification X = resistor, Y = pure inductor, Z = pure capacitor would require $\pi/2$ in the latter two cases. The series LCR derivation below uses the total resistance, including any internal resistances.

Step 3: Conclusion X is resistive, Y is inductive in nature, and Z is capacitive in nature. The printed $\pi/4$ does not uniquely identify pure ideal L and C; it requires a resistive contribution in the simple series model.

Quick Tip to Solve: A voltage lead signals inductive behaviour; a current lead signals capacitive behaviour. A 45-degree shift includes resistance.

32(a)(ii). Establish the expression for impedance of circuit when elements X, Y and Z are connected in series to an ac source. Show the variation of current in the circuit with the frequency of the applied ac source.

Solution:

Concept:

- For series LCR, $X_L = \omega L$, $X_C = 1/(\omega C)$, and $\tan \phi = (X_L - X_C)/R$, with $\omega = 2\pi f$ and R the total series resistance.
- Average power is $P = V_{\text{rms}} I_{\text{rms}} \cos \phi$. Resonance occurs when the inductive and capacitive reactances cancel.

Step 1: Add the voltage phasors In a series circuit the same rms current I flows through every component. Choose it as the phasor reference. The resistive voltage $V_R = IR$ is along I , the inductive voltage $V_L = IX_L$ leads it by 90° , and the capacitive voltage $V_C = IX_C$ lags it by 90° . The last two are opposite; their resultant is perpendicular to V_R . Therefore

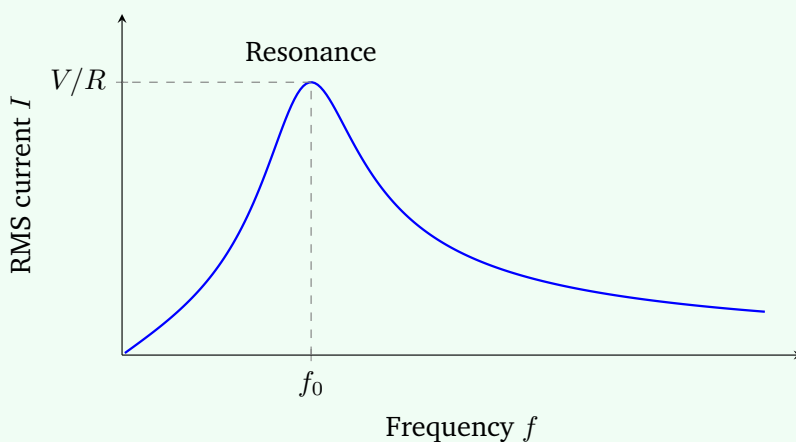
$$\begin{aligned} V^2 &= V_R^2 + (V_L - V_C)^2 \\ &= I^2 [R^2 + (X_L - X_C)^2], \\ Z = \frac{V}{I} &= \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}. \end{aligned}$$

For the model in part (i), $R = R_X + R_Y + R_Z$. This equation also covers ideal L and C connected with an external resistor.

Step 2: Describe the frequency response Keeping the rms source voltage V , R , L , and C fixed gives

$$I(f) = \frac{V}{\sqrt{R^2 + \left(2\pi fL - \frac{1}{2\pi fC}\right)^2}}.$$

At low frequency, capacitive reactance is large and current is small. As frequency approaches $f_0 = 1/(2\pi\sqrt{LC})$, the reactances cancel and the current reaches $I_{\text{max}} = V/R$. At higher frequency, inductive reactance dominates and current decreases. The graph shows this resonance peak for a finite positive resistance.



Current versus frequency at fixed source voltage; the peak occurs at resonance.

Step 3: Conclusion The series impedance is $Z = \sqrt{R^2 + (\omega L - 1/(\omega C))^2}$. At fixed rms voltage, the

current peaks at $f_0 = 1/(2\pi\sqrt{LC})$, with $I_{\max} = V/R$.

Quick Tip to Solve: Subtract the inductive and capacitive voltage phasors before combining their resultant with the perpendicular resistive voltage.

In a series LCR circuit, obtain the conditions under which

32(a)(iii)(i). impedance is minimum.

Solution:

Concept:

- For series LCR, $X_L = \omega L$, $X_C = 1/(\omega C)$, and $\tan \phi = (X_L - X_C)/R$, with $\omega = 2\pi f$ and R the total series resistance.
- Average power is $P = V_{\text{rms}} I_{\text{rms}} \cos \phi$. Resonance occurs when the inductive and capacitive reactances cancel.

Step 1: Write the frequency-dependent impedance The series LCR circuit has $Z^2 = R^2 + (X_L - X_C)^2$, with $X_L = \omega L$ and $X_C = 1/(\omega C)$. For fixed resistance, the only frequency-dependent contribution is the square of the net reactance. It cannot be negative, so $Z \geq R$.

Step 2: Find the minimum impedance Since $(\omega L - 1/\omega C)^2 \geq 0$, impedance is minimum when

$$\omega_0 L = \frac{1}{\omega_0 C}, \quad \omega_0 = \frac{1}{\sqrt{LC}}, \quad Z_{\min} = R.$$

At resonance voltage and current are in phase, so the power factor is one. Resonance therefore does not give wattless current in a circuit with positive resistance.

Step 3: Conclusion Minimum impedance occurs at resonance: $\boxed{\omega_0 L = 1/(\omega_0 C)}$, or $\omega_0 = 1/\sqrt{LC}$; then $Z_{\min} = R$.

Quick Tip to Solve: Minimise impedance by setting the squared net reactance to zero; the resistance remains even at resonance.

32(a)(iii)(ii). wattless current flows in the circuit.

Solution:

Concept:

- For series LCR, $X_L = \omega L$, $X_C = 1/(\omega C)$, and $\tan \phi = (X_L - X_C)/R$, with $\omega = 2\pi f$ and R the total series resistance.
- Average power is $P = V_{\text{rms}} I_{\text{rms}} \cos \phi$. Resonance occurs when the inductive and capacitive reactances cancel.

Step 1: Express the average power For sinusoidal voltage and current, the cycle-averaged power is $P = V_{\text{rms}} I_{\text{rms}} \cos \phi$. Wattless current means a nonzero alternating current with zero average energy consumption. In an ideal reactive element, energy is stored temporarily in an electric or magnetic field and returned to the source.

Step 2: Obtain the wattless-current condition Nonzero current is wattless if $P = VI \cos \phi = 0$, which requires $\cos \phi = 0$, or $\phi = \pm\pi/2$. In series LCR, $\cos \phi = R/Z$ and $P = I^2 R$; thus exact wattless current

requires zero resistance and nonzero net reactance:

$$R = 0, \quad \omega L \neq \frac{1}{\omega C}.$$

The circuit is then purely reactive and returns the stored energy to the source each cycle. With any positive series resistance the current cannot be exactly wattless. Ideal zero resistance at resonance is excluded: the impedance vanishes and the ordinary finite-current steady-state formula is singular.

Step 3: Conclusion Nonzero wattless current requires $\cos \phi = 0$, so $\phi = \pm\pi/2$. In series LCR this means $R = 0$ and $\omega L \neq 1/(\omega C)$; positive resistance prevents exactly wattless current.

Quick Tip to Solve: Use average power $I^2 R$: resonance removes reactance, whereas wattless current requires the resistive loss to vanish.

OR

32(b)(i). Describe the construction and working of a transformer and hence obtain the relation for $\left(\frac{v_s}{v_p}\right)$ in terms of number of turns of primary and secondary. [5 marks total]

Solution:

Concept:

- A transformer changes an alternating voltage by mutual induction: a changing current in the primary produces changing magnetic flux linking the secondary.
- Faraday's law gives $e = -N d\Phi/dt$, where N is the number of turns and Φ is the magnetic flux through each turn.
- For an ideal transformer, all turns of both windings link the same flux, winding resistance is negligible, and core losses are absent. The voltage ratio is therefore the turns ratio.

Step 1: Describe the construction A transformer has two coils of insulated copper wire wound on a common closed core of soft iron or suitable magnetic material. The primary has N_p turns and is connected to the ac supply; the secondary has N_s turns and is connected to the load. The coils are electrically insulated from one another and from the core, but are magnetically coupled through it. The core provides a low-reluctance path for flux and is made of thin insulated laminations to reduce eddy currents.

Step 2: Explain the working by mutual induction The alternating voltage applied to the primary drives an alternating magnetising current. It produces an alternating flux $\Phi(t)$ in the core, which links the primary and secondary turns. This induces an emf in each winding. When the secondary circuit is closed, its induced emf drives current through the load and transfers energy from the primary supply to the load through the magnetic field. Continuous transformer action needs changing flux; a steady dc supply cannot maintain an induced secondary emf.

Step 3: Derive the voltage ratio Applying Faraday's law to the two windings with a consistent winding sense gives

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

Since both link the same flux, their induced emf magnitudes are in the ratio N_s/N_p . More explicitly,

for sinusoidal flux $\Phi = \Phi_m \sin \omega t$, their rms emfs are

$$E_p = \frac{N_p \omega \Phi_m}{\sqrt{2}}, \quad E_s = \frac{N_s \omega \Phi_m}{\sqrt{2}}.$$

With negligible winding resistance and leakage, the terminal rms voltage magnitudes satisfy $V_p = E_p$ and $V_s = E_s$. Dividing yields

$$\frac{V_s}{V_p} = \frac{E_s}{E_p} = \frac{N_s}{N_p}.$$

Thus $N_s > N_p$ gives a step-up transformer, while $N_s < N_p$ gives a step-down transformer. The frequency of the secondary voltage equals the supply frequency.

Step 4: Conclusion A transformer operates by mutual induction. For ideal common flux and negligible winding voltage drops, $V_s/V_p = N_s/N_p$, with voltages interpreted as rms magnitudes.

Quick Tip to Solve: Apply Faraday's law to each winding using the same flux per turn; division cancels the common time derivative.

32(b)(ii). Discuss four main causes of energy loss in a real transformer.

Solution:

Concept:

- A transformer changes an alternating voltage by mutual induction: a changing current in the primary produces changing magnetic flux linking the secondary.
- For an ideal transformer, all turns of both windings link the same flux, winding resistance is negligible, and core losses are absent. The voltage ratio is therefore the turns ratio.

Step 1: Explain resistive heating in windings and core Copper loss: The primary and secondary wires have finite resistance, so electrical energy becomes heat at the rate $I_p^2 R_p + I_s^2 R_s$. Low-resistance, adequately thick copper wire reduces this loss.

Eddy-current loss: Changing flux induces circulating currents in the conducting core; these heat the core. Thin core laminations insulated from one another interrupt the current paths and increase their resistance.

Step 2: Explain magnetic losses and leakage Hysteresis loss: The alternating field repeatedly magnetises and demagnetises the core. Energy equal to the area of its hysteresis loop per unit volume is dissipated in each cycle. A material with a narrow hysteresis loop, such as suitable soft iron or silicon steel, reduces this loss.

Flux leakage: Some primary flux does not link the secondary, so the magnetic coupling is imperfect and the available secondary voltage is reduced. A closed core of high magnetic permeability and closely coupled windings minimise leakage. Leakage chiefly causes imperfect transfer and voltage regulation rather than directly heating an ideal lossless core; it is conventionally included among the four causes of non-ideal transformer performance.

Step 3: Conclusion The four standard causes of non-ideal transformer performance are copper loss, eddy-current loss, hysteresis loss and flux leakage.

Quick Tip to Solve: Recall the four locations or processes: winding resistance, circulating core currents, repeated magnetisation and incomplete flux linkage.

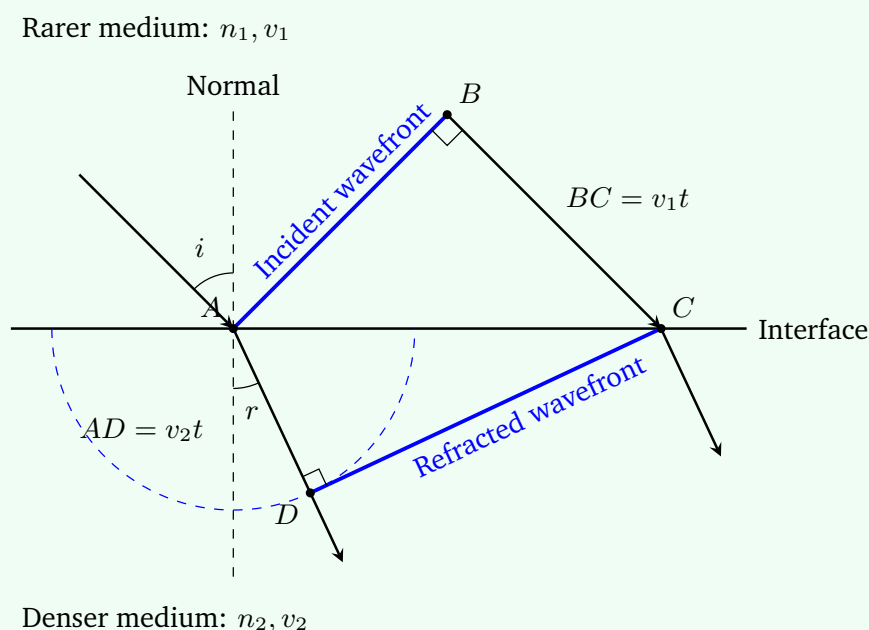
33(a)(i). A plane light wave propagating from a rarer into a denser medium, is incident at an angle i on the surface separating two media. Using Huygen's principle, draw the refracted wave and hence verify Snell's law of refraction. [5 marks total]

Solution:

Concept:

- Huygens' principle: every point on a wavefront emits secondary wavelets; their forward common tangent gives the later wavefront. Rays are perpendicular to wavefronts.
- For light speeds v_1, v_2 and refractive indices n_1, n_2 , $v = c/n$. Refraction angles i and r are measured from the normal to the interface.

Step 1: Construct the refracted wavefront Let AB be a plane incident wavefront, with point A reaching the interface first. The rarer medium has speed v_1 ; the denser medium has speed $v_2 < v_1$. During a time t , point B travels along its incident ray to C , so $BC = v_1t$. In the same time, the secondary wavelet emitted from A into the denser medium acquires radius $AD = v_2t$. Draw the tangent CD from C to this wavelet. It is the refracted plane wavefront. The radius AD is perpendicular to CD and gives the direction of a refracted ray; likewise, BC is perpendicular to AB . The dashed line at A is the normal to the interface.



Huygens' construction: incident wavefront AB and refracted wavefront CD ; the wavelet radius AD is perpendicular to CD .

Step 2: Obtain Snell's law from the construction Since the angle between two lines equals the angle between their respective perpendiculars, $\angle BAC = i$ and $\angle DCA = r$. Right triangles ABC and ADC , which share hypotenuse AC , therefore give

$$\sin i = \frac{BC}{AC} = \frac{v_1 t}{AC}, \quad \sin r = \frac{AD}{AC} = \frac{v_2 t}{AC}.$$

Dividing eliminates both the time and the common construction length:

$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \frac{c/n_1}{c/n_2} = \frac{n_2}{n_1}, \quad n_1 \sin i = n_2 \sin r.$$

This verifies Snell's law. As $n_2 > n_1$, it also gives $r < i$: the refracted ray bends towards the normal, as shown in the drawing.

Step 3: Conclusion The tangent CD is the refracted wavefront. Huygens' construction gives $n_1 \sin i = n_2 \sin r$; because $n_2 > n_1$, the refracted ray bends towards the normal.

Quick Tip to Solve: Use the common hypotenuse AC in both right triangles and divide the sine ratios to cancel the elapsed time.

33(a)(ii). In a Young's double slit experiment, the slits are separated by 0.30 mm and the screen is kept 1.5 m away. The wavelength of light used is 600 nm. Calculate the distance between the central bright fringe and the 4th dark fringe.

Solution:

Concept:

- In Young's double-slit experiment, fringe width is $\beta = \lambda L/d$, where L is screen distance, d slit separation and λ wavelength. The m -th dark fringe from the central bright fringe lies at $y_m = (m - \frac{1}{2})\beta$.
- Destructive interference occurs when the two slit waves differ in phase by an odd multiple of π , corresponding to path difference $(m - \frac{1}{2})\lambda$.

Step 1: Calculate the fringe width Convert all given lengths to SI units before substitution:

$$d = 0.30 \times 10^{-3} \text{ m}, \quad L = 1.5 \text{ m}, \quad \lambda = 600 \times 10^{-9} \text{ m}.$$

As $L \gg d$, the usual small-angle formula applies:

$$\beta = \frac{\lambda L}{d} = \frac{(600 \times 10^{-9})(1.5)}{0.30 \times 10^{-3}} = 3.0 \times 10^{-3} \text{ m} = 3.0 \text{ mm}.$$

Step 2: Locate the fourth dark fringe Destructive interference occurs when the path difference is an odd multiple of $\lambda/2$. Counting dark fringes outwards from the central bright fringe, the first is at $\beta/2$, the second at $3\beta/2$, and the fourth at $7\beta/2$. Thus use $m = 4$, not the bright-fringe relation $y = m\beta$:

$$y_4 = \left(4 - \frac{1}{2}\right)\beta = \frac{7}{2}(3.0 \text{ mm}) = 10.5 \text{ mm}.$$

The fourth dark fringe occurs symmetrically on either side of the central maximum; the question asks for the magnitude of its distance.

Step 3: Conclusion The distance from the central bright fringe to the fourth dark fringe is $10.5 \text{ mm} = 1.05 \times 10^{-2} \text{ m}$.

Quick Tip to Solve: Dark fringes start half a fringe width from the centre, so the fourth dark fringe is at 3.5 times the fringe width.

33(b)(i). Discuss briefly diffraction of light from a single slit and draw the shape of the diffraction pattern. [5 marks total]

Solution:

Concept:

- Diffraction is the spreading of light into the geometrical shadow of an aperture. By Huygens' principle, different parts of a slit act as coherent secondary sources whose waves interfere.
- For a slit of width a illuminated normally by monochromatic light of wavelength λ , the path difference between waves from the extreme edges in direction θ is $a \sin \theta$.

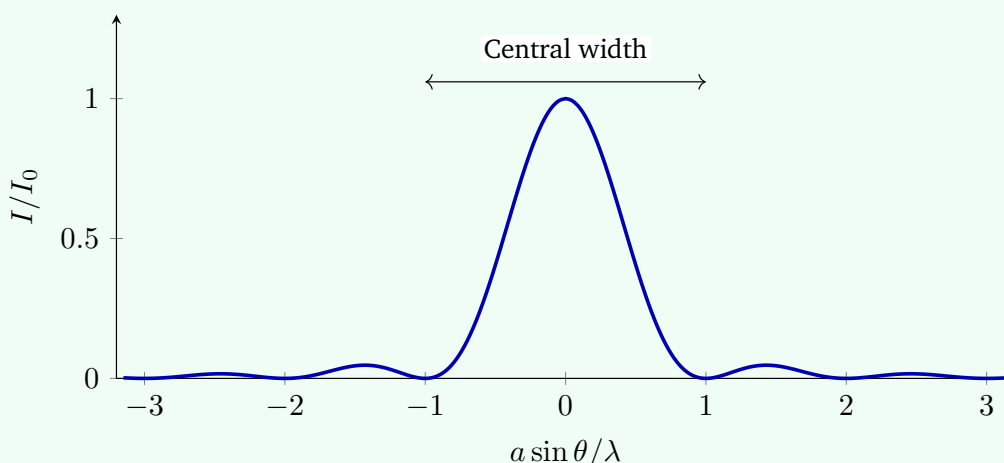
Step 1: Explain the origin of the diffraction pattern Allow a parallel beam of monochromatic light to fall normally on a narrow single slit, and observe the far-field pattern on a distant screen or in the focal plane of a convex lens. The light spreads beyond the geometrical image of the slit. Its different portions emit coherent secondary wavelets, which superpose at the observation point. At the centre, $\theta = 0$, all portions have equal optical paths, so their contributions reinforce and produce the brightest maximum. For the first minimum, divide the slit into two equal halves. If $a \sin \theta = \lambda$, each point in one half can be paired with a point in the other half whose path difference is $\lambda/2$. The pairs cancel. More generally, dividing the slit into $2n$ equal strips gives the minima at

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

Step 2: Describe and sketch the intensity distribution Between successive minima there are secondary bright maxima. They are much weaker than the central maximum and decrease in intensity away from it. The pattern is symmetric about the centre. Its intensity variation is

$$I = I_0 \left(\frac{\sin \beta}{\beta} \right)^2, \quad \beta = \frac{\pi a \sin \theta}{\lambda},$$

with the limiting value $I = I_0$ at $\beta = 0$. The central bright maximum extends between the first minima on either side. For small angles its angular width is $2\lambda/a$, twice the width λ/a of each adjacent secondary maximum between successive minima. On a distant screen a distance D away, the central width is $2D\lambda/a$. The graph shows the wide central peak and the weak side maxima; its horizontal coordinate is dimensionless.



Single-slit intensity pattern; successive integer positions are minima, and the central maximum has twice the width of a secondary maximum.

Step 3: Conclusion The single-slit pattern has a broad bright central maximum and weaker secondary maxima on both sides. Minima satisfy $a \sin \theta = \pm n\lambda$; the central angular width is approximately $2\lambda/a$.

Quick Tip to Solve: Place the first minima at plus and minus wavelength divided by slit width; their separation sets the central peak width.

33(b)(ii). An object is placed between the pole and the focus of a concave mirror. Using mirror formula, prove mathematically that it produces a virtual and an enlarged image.

Solution:

Concept:

- The mirror formula is $1/f = 1/v + 1/u$, and linear magnification is $m = -v/u$. Here f , u and v are signed focal, object and image distances measured from the pole.
- Under the Cartesian convention, a real object in front of the mirror has $u < 0$; a concave mirror has $f < 0$. An image behind the mirror has $v > 0$ and is virtual.

Step 1: Apply the mirror formula with Cartesian signs Take the direction of incident light as positive and the pole as origin. A concave mirror has $f = -F$, where $F > 0$ is the magnitude of its focal length. For a real object between the pole and focus, write $u = -x$, with $0 < x < F$. Substituting in the mirror formula gives

$$\begin{aligned} -\frac{1}{F} &= \frac{1}{v} - \frac{1}{x}, \\ \frac{1}{v} &= \frac{1}{x} - \frac{1}{F} = \frac{F-x}{Fx}, \\ v &= \frac{Fx}{F-x}. \end{aligned}$$

Both the numerator and denominator are positive, so the image distance is positive. The image therefore lies behind the mirror, where only the backward extensions of reflected rays meet; it is virtual.

Step 2: Establish the image size and orientation Use the signed distances in the magnification

formula:

$$m = -\frac{v}{u} = -\frac{Fx/(F-x)}{-x} = \frac{F}{F-x}.$$

Since $0 < x < F$, the denominator satisfies $0 < F - x < F$. Thus $m > 1$: the image height is greater than the object height. The positive sign of m also shows that the image is erect. This result holds for every object position strictly between the pole and the focus.

Step 3: Conclusion For $0 < x < F$, $v = Fx/(F-x) > 0$ and $m = F/(F-x) > 1$. Thus the image lies behind the mirror and is virtual, erect and enlarged.

Quick Tip to Solve: Write the concave focal length as negative and constrain the object distance before evaluating the signs of v and magnification.