

CBSE Class 12 Physics Question Paper 2024 with Solution PDF-Set 55/4/3

Question Paper with Solutions

Conducted by the Central Board of Secondary Education (CBSE)



Time Allowed: 3 hours

Maximum Marks: 70

General Instructions

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

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

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

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

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

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

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

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

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

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

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

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

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

Section A (16 marks)

1. An electric dipole of dipole moment $\vec{p}$ is kept in a uniform electric field $\vec{E}$. The amount of work done to rotate it from the position of stable equilibrium to that of unstable equilibrium will be [1 mark]

- (A) $2pE$
- (B) $-2pE$
- (C) pE
- (D) zero

Correct Answer: (A) $2pE$

Solution:

Concept:

- The potential energy of a dipole is $U = -pE \cos \theta$, where θ is the angle between its dipole moment and the electric field.
- For slow rotation, external work equals the increase in potential energy: $W_{\text{ext}} = U_f - U_i$.

Step 1: Identify the two equilibrium positions Stable equilibrium has the dipole aligned with the field, so $\theta_i = 0$ and $U_i = -pE$. Unstable equilibrium has the dipole opposite to the field, so $\theta_f = \pi$ and $U_f = +pE$.

Step 2: Calculate the energy increase The external agent supplies energy while turning the dipole against the restoring torque. Thus

$$W_{\text{ext}} = (+pE) - (-pE) = 2pE.$$

The value $-2pE$ is the work done by the electric field. The value pE corresponds to a rotation only up to 90° ; zero torque at the endpoints does not imply zero total work.

Step 3: Conclusion The required external work is $2pE$. Hence, the correct option is (A).

Quick Tip to Solve: For a stable-to-unstable rotation, use the energy change from $-pE$ to $+pE$, not the torque at either endpoint.

2. An infinite long straight wire having a charge density λ is kept along $y'y$ axis in x - y plane. The Coulomb force on a point charge q at a point $P(x, 0)$ will be [1 mark]

- (A) attractive and $\frac{\lambda q}{2\pi\epsilon_0 x}$
(B) repulsive and $\frac{\lambda q}{2\pi\epsilon_0 x}$
(C) attractive and $\frac{\lambda q}{\pi\epsilon_0 x}$
(D) repulsive and $\frac{\lambda q}{\pi\epsilon_0 x}$

Correct Answer: (B) repulsive and $\frac{\lambda q}{2\pi\epsilon_0 x}$

Solution:

Concept:

- An infinite straight wire with linear charge density λ produces a radial field of magnitude $E = |\lambda|/(2\pi\epsilon_0 r)$ at perpendicular distance r .
- A point charge experiences $\vec{F} = q\vec{E}$; like signs repel and unlike signs attract.

Step 1: Apply cylindrical symmetry The wire lies on the y -axis, so the perpendicular distance of $P(x, 0)$ is $|x|$. For the positive quantities convention used in the options, take $x > 0$, $\lambda > 0$ and $q > 0$. Gauss's law on a cylinder of length L gives

$$E(2\pi xL) = \frac{\lambda L}{\epsilon_0}.$$

Step 2: Find the force and its direction Multiplying the field by the point charge gives

$$F = qE = \frac{\lambda q}{2\pi\epsilon_0 x}.$$

The field points away from a positively charged wire, so the positive test charge is repelled. Option (A) has the opposite direction; options (C) and (D) are twice the correct magnitude. If opposite charge signs were specified, the force would instead be attractive; that is not the positive-charge convention underlying these options.

Step 3: Conclusion For positive λ and q , the force is repulsive and has magnitude $\lambda q/(2\pi\epsilon_0 x)$. Hence, the correct option is (B).

Quick Tip to Solve: Use the perpendicular distance to the wire and the cylindrical area $2\pi rL$; then determine direction from the signs of the charges.

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

- (A) zero
- (B) π
- (C) $\frac{\pi}{2}$
- (D) $\frac{\pi}{4}$

Correct Answer: (A) zero

Solution:

Concept:

- In a plane electromagnetic wave, the electric and magnetic fields oscillate in phase.
- For propagation along $+z$, one choice is $\vec{E} = E_0 \cos(kz - \omega t)\hat{x}$ and $\vec{B} = B_0 \cos(kz - \omega t)\hat{y}$, with $E_0 = cB_0$ in vacuum.

Step 1: Compare the oscillations The time-and-position dependent argument $kz - \omega t$ is the same for both fields. At a fixed point they reach zero together, attain positive maxima together and reverse together. Their temporal phase difference therefore vanishes.

Step 2: Distinguish phase from direction The fields are mutually perpendicular in space, but this is an angle between vectors, not a time delay between oscillations. Thus the tempting value $\pi/2$ confuses spatial orientation with phase. A difference of π would make the signed components opposite in phase, and $\pi/4$ would introduce a delay absent from the plane-wave equations.

Step 3: Conclusion The phase difference is zero. Hence, the correct option is (A).

Quick Tip to Solve: Compare the sine or cosine arguments of the two fields; perpendicular vector directions do not mean a quarter-cycle phase difference.

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

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

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

Solution:

Concept:

- For the Balmer series, electrons fall to $n_f = 2$ from $n = 3, 4, 5, \dots$, and $1/\lambda_n = R_H(1/4 - 1/n^2)$.
- As the upper level increases, the lines converge toward a finite series limit; the higher members of the observed series become progressively weaker.

Step 1: Compare neighbouring wavelengths Increasing n reduces $1/n^2$, so $1/\lambda_n$ increases toward $R_H/4$ and the wavelength decreases toward $4/R_H$. Also,

$$\frac{1}{\lambda_{n+1}} - \frac{1}{\lambda_n} = R_H \left(\frac{1}{n^2} - \frac{1}{(n+1)^2} \right),$$

which tends to zero. The spectral lines consequently crowd together near the short-wavelength limit.

Step 2: Include the observed intensity trend The higher members of the Balmer series are weaker. Line intensity concerns how much radiation is emitted in a transition; it cannot be inferred merely from the larger energy of each photon. Options (A) and (B) contradict convergence, while (C) gives the wrong intensity trend for the series described.

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

Quick Tip to Solve: For a spectral series, identify the fixed final level and let the initial level grow: the lines crowd toward the short-wavelength limit.

5. Two long straight parallel conductors A and B, kept at a distance r , carry current I in opposite directions. A third identical conductor C, kept at a distance $\left(\frac{r}{3}\right)$ from A carry a current I_1 in the same direction as in A. The net magnetic force on unit length of C is [1 mark]

- (A) $\frac{3\mu_0 II_1}{2\pi r}$, towards A
(B) $\frac{3\mu_0 II_1}{2\pi r}$, towards B
(C) $\frac{3\mu_0 II_1}{4\pi r}$, towards A
(D) $\frac{3\mu_0 II_1}{4\pi r}$, towards B

Correct Answer: No unique correct option: C is not fully located, and neither usual collinear interpretation matches the printed options.

Solution:

Concept:

- Two parallel currents I and I_1 , separated by d , exert force per unit length $f = \mu_0 II_1 / (2\pi d)$.
- Currents in the same direction attract; opposite currents repel. Forces from the two conductors must be added as vectors.

Step 1: Use the separation actually printed The printed separation is $AC = r/3$, and C carries I_1 . Thus A attracts C with

$$f_{AC} = \frac{3\mu_0 II_1}{2\pi r}.$$

This alone matches the magnitude in (A), but it omits the nonzero force exerted by B. The question gives no diagram or statement fixing C relative to the line joining A and B.

Step 2: Test the usual collinear interpretations If C lies between A and B, $BC = 2r/3$. Both attraction toward A and repulsion away from B point toward A, so

$$f_{\text{net}} = \frac{\mu_0 II_1}{2\pi} \left(\frac{3}{r} + \frac{3}{2r} \right) = \frac{9\mu_0 II_1}{4\pi r}.$$

If C lies beyond A, away from B, $BC = 4r/3$, and the forces oppose:

$$f_{\text{net}} = \frac{\mu_0 II_1}{2\pi} \left(\frac{3}{r} - \frac{3}{4r} \right) = \frac{9\mu_0 II_1}{8\pi r} \quad \text{toward A.}$$

Neither result is printed. Non-collinear placements require further positional information and need

not give a force toward A or B.

Step 3: Conclusion The printed data do not determine a unique net force, and neither usual collinear placement gives a listed value. No unique option is defensible as printed.

Quick Tip to Solve: Calculate both wire forces using their separate distances before adding them; a value matching only the force from A is not the net force.

6. A coil of N turns is placed in a magnetic field $\vec{B}$ such that $\vec{B}$ is perpendicular to the plane of the coil. $\vec{B}$ changes with time as $B = B_0 \cos\left(\frac{2\pi}{T}t\right)$ where T is the time period. The magnitude of induced emf in the coil will be maximum at (here, $n = 1, 2, 3, 4, \dots$) [1 mark]

- (A) $t = \frac{nT}{8}$
(B) $t = \frac{nT}{4}$
(C) $t = \frac{nT}{2}$
(D) $t = nT$

Correct Answer: Intended option (B) requires odd n ; with the printed $n=1,2,3,\dots$ none of the options is fully correct.

Solution:

Concept:

- Faraday's law gives $\varepsilon = -N d\Phi/dt$, where $\Phi = AB$ for a uniform field normal to a fixed coil of area A .
- The magnitude of a sinusoid is maximal when its sine or cosine factor has absolute value one.

Step 1: Differentiate the magnetic flux Using the given field,

$$\Phi = AB_0 \cos\left(\frac{2\pi t}{T}\right), \quad \varepsilon = \frac{2\pi NAB_0}{T} \sin\left(\frac{2\pi t}{T}\right).$$

The induced emf depends on how fast the field changes, so it is zero, not maximum, when the magnetic field is at an extremum.

Step 2: Find every time of maximum magnitude The condition is $|\sin(2\pi t/T)| = 1$. Therefore

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

Option (B), $nT/4$, describes these times only for odd n . The paper explicitly prints $n = 1, 2, 3, 4, \dots$, so its even values give zero emf. Option (A) includes nonmaximal times such as $T/8$, while (C) and (D) give zero emf for every printed integer n .

Step 3: Conclusion Maxima occur at odd multiples of $T/4$. Option (B) is the intended choice with n restricted to odd positive integers; with the printed unrestricted sequence, no option is fully correct.

Quick Tip to Solve: Differentiate the field first, then solve for the absolute value of the sine to equal one; consecutive magnitude maxima are separated by $T/2$.

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

[1 mark]

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

Correct Answer: (A) R

Solution:

Concept:

- The magnetic field at the centre of a circular loop of radius R carrying current I is $B = \mu_0 I / (2R)$.
- For a small concentric loop, the field is approximately uniform over its area, so $\Phi \simeq B\pi r^2$, with $r = R/20$.

Step 1: Find the area of the smaller loop The smaller loop radius changes with R ; it is not a fixed independent length. Its area is

$$A_B = \pi \left(\frac{R}{20} \right)^2 = \frac{\pi R^2}{400}.$$

Because the loops are coplanar, the magnetic field is normal to the smaller loop and no further cosine factor is needed.

Step 2: Combine field and area The field scales as $1/R$ for fixed current, whereas the area scales as R^2 . Hence

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

The centre-field approximation affects the coefficient slightly, not the scaling: at a fixed radius ratio, the exact field distribution also scales as $1/R$. Option (D) includes only the area dependence; (B) and (C) give powers unsupported by the field-times-area calculation.

Step 3: Conclusion For fixed current, the magnetic flux is proportional to R . Hence, the correct option is (A).

Quick Tip to Solve: When both loops scale together, multiply the field scaling R^{-1} by the area scaling R^2 to get the flux scaling.

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

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

Correct Answer: As printed, the ammeter reaches full scale at 1 A, which is absent from the options. Option (B) is the galvanometer current.

Solution:

Concept:

- An ammeter made from a galvanometer has a low shunt resistance S in parallel with the galvanometer resistance G .
- Equal branch voltages give $I_g G = (I - I_g)S$, where I is total ammeter current and I_g is galvanometer current at full scale.

Step 1: Distinguish the two currents The stated ammeter range is 0–1 A. Therefore its total full-scale current is already specified as $I = 1\ \text{A}$. None of the printed options gives this value; even option (D), 0.1 A, is only one tenth of full scale.

Step 2: Calculate the galvanometer current implied by the options Using $G = 100\ \Omega$ and $S = 0.1\ \Omega$, the much smaller current through the galvanometer is

$$I_g = \frac{IS}{G + S} = \frac{1 \times 0.1}{100 + 0.1}\ \text{A} \simeq 9.99 \times 10^{-4}\ \text{A} \simeq 1\ \text{mA}.$$

This matches option (B); options (A) and (C) are respectively a factor of about ten too small and too large for this branch current. Thus (B) is the intended result if the last sentence means the galvanometer, but it is not the total current through the ammeter as printed.

Step 3: Conclusion The printed wording has no correct listed option: the ammeter full-scale current is 1 A. The galvanometer full-scale current is approximately 1 mA, corresponding to intended option (B).

Quick Tip to Solve: In a shunted galvanometer, first label total current and coil current separately; the stated ammeter range refers to their total.

9. The r.m.s. value of a current given by $i = (i_1 \cos \omega t + i_2 \sin \omega t)$ is

[1 mark]

- (A) $\frac{1}{\sqrt{2}}(i_1 + i_2)$
(B) $\frac{1}{\sqrt{2}}(i_1 - i_2)$
(C) $\frac{1}{\sqrt{2}}\sqrt{i_1^2 + i_2^2}$
(D) $\frac{1}{\sqrt{2}}(i_1^2 + i_2^2)$

Correct Answer: (C) $\frac{1}{\sqrt{2}}\sqrt{i_1^2 + i_2^2}$

Solution:

Concept:

- The root-mean-square current is $I_{\text{rms}} = \sqrt{\langle i^2 \rangle}$, with the average taken over a complete cycle.
- Over a cycle, $\langle \cos^2 \omega t \rangle = \langle \sin^2 \omega t \rangle = 1/2$, while $\langle \sin \omega t \cos \omega t \rangle = 0$.

Step 1: Square the instantaneous current The two given components have the same frequency and a phase difference of $\pi/2$. Expanding their sum before averaging gives

$$i^2 = i_1^2 \cos^2 \omega t + i_2^2 \sin^2 \omega t + 2i_1 i_2 \sin \omega t \cos \omega t.$$

Step 2: Average and take the square root The cross term averages to zero, so

$$\langle i^2 \rangle = \frac{i_1^2 + i_2^2}{2}, \quad I_{\text{rms}} = \frac{\sqrt{i_1^2 + i_2^2}}{\sqrt{2}}.$$

Options (A) and (B) add or subtract amplitudes as though the components were in phase or opposite in phase. Here they are in quadrature. Option (D) omits the square root of the sum of squares and has units of current squared, so it cannot represent an r.m.s. current.

Step 3: Conclusion $I_{\text{rms}} = \frac{1}{\sqrt{2}}\sqrt{i_1^2 + i_2^2}$. Hence, the correct option is (C).

Quick Tip to Solve: For sine and cosine currents of the same frequency, combine their amplitudes by Pythagoras before dividing by $\sqrt{2}$.

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

[1 mark]

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

Correct Answer: Both (A) and (B) are valid for a given metal; the printed single-choice question has no unique correct option.

Solution:

Concept:

- Light transfers energy in photons of energy $h\nu$, where h is Planck's constant and ν is frequency.

- Einstein's photoelectric equation is $K_{\max} = h\nu - \phi$, where ϕ is the work function of the emitting metal.

Step 1: Check the threshold and kinetic-energy statements Emission requires $h\nu \geq \phi$; the threshold frequency is $\nu_0 = \phi/h$. Below this frequency no photoelectrons are emitted in the usual photoelectric experiment, so (A) is correct. For a given metal, ϕ is fixed and $K_{\max} = h\nu - \phi$ depends on frequency and not on intensity. Thus (B) also states a standard photoelectric observation correctly. Across different metals the work function also matters, but the usual experiment compares frequencies for one metal.

Step 2: Test the remaining statements Photoemission begins without an observable time lag when suitable radiation reaches the surface, so the delayed emission claimed in (C) is false. At fixed frequency above threshold, greater incident intensity gives more photons per second and hence more emitted electrons. The photoelectric current therefore depends on intensity under the usual collection conditions, contrary to (D).

Step 3: Conclusion Both (A), the threshold-frequency observation, and (B), the frequency dependence of maximum kinetic energy for a given metal, are explained by photon theory. The printed question does not admit a unique single correct option.

Quick Tip to Solve: Use $K_{\max} = h\nu - \phi$ for electron energy and photon arrival rate for current; these distinguish frequency effects from intensity effects.

11. The magnetic susceptibility for a diamagnetic material is

[1 mark]

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

Correct Answer: (A) small and negative

Solution:

Concept:

- Magnetic susceptibility χ_m relates magnetisation M to magnetic field intensity H through $M = \chi_m H$.
- A diamagnetic material acquires weak induced magnetisation opposite to the applied field.

Step 1: Determine the sign of susceptibility Taking the applied field direction as positive, the induced magnetisation of a diamagnet is negative. The relation $\chi_m = M/H$ therefore requires $\chi_m < 0$. Positive susceptibility describes magnetisation along the field, so options (B) and (D) are excluded.

Step 2: Compare its magnitude with unity Ordinary diamagnetic substances respond only weakly to the applied field, so $|\chi_m| \ll 1$. Their relative permeability $\mu_r = 1 + \chi_m$ is slightly less than unity. A large negative susceptibility, as claimed in (C), does not describe the usual diamagnetic materials in this classification.

Step 3: Conclusion The magnetic susceptibility is small and negative. Hence, the correct option is (A).

Quick Tip to Solve: For ordinary diamagnets, remember opposition means a negative sign and weak repulsion means a small magnitude.

12. The radius (r_n) of n^{th} orbit in Bohr model of hydrogen atom varies with n as

[1 mark]

- (A) $r_n \propto n$
- (B) $r_n \propto \frac{1}{n}$
- (C) $r_n \propto n^2$
- (D) $r_n \propto \frac{1}{n^2}$

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

Solution:

Concept:

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

Step 1: Eliminate the orbital speed From angular-momentum quantisation, $v_n = n\hbar/(m_e r_n)$. Substitute this into the force equation to obtain

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

Step 2: Identify the dependence on the quantum number Rearrangement gives

$$r_n = \frac{\hbar^2}{m_e k e^2} n^2 = a_0 n^2.$$

The Bohr radius a_0 is constant for hydrogen, so the radius increases quadratically with n . Option (A) has the wrong power, while (B) and (D) wrongly predict shrinking orbits as n increases. The inverse-square dependence in (D) is associated with the magnitude of energy, not the radius.

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

Quick Tip to Solve: Keep Bohr scalings distinct: radius grows as n^2 , whereas the magnitude of orbital energy falls as $1/n^2$.

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

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

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

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

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

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

Solution:

Concept:

- Free electrons have large random velocities whose vector average vanishes without an applied electric field.
- An applied electric field adds a small average drift velocity $\vec{v}_d$; conventional current is opposite to electron drift.

Step 1: Evaluate the assertion The assertion is true. A net drift is an ensemble average and does not require every electron to have the same instantaneous direction of motion. Individual electrons continue to move in many directions and undergo collisions inside the conductor.

Step 2: Evaluate the reason The reason is true. One may describe an electron's instantaneous velocity as a fluctuating random part plus the small drift contribution:

$$\vec{v} = \vec{v}_{\text{random}} + \vec{v}_d.$$

The random velocities are much larger in magnitude than the drift velocity, even though their ensemble average is zero.

Step 3: Check the explanatory link Because the small directed drift is superposed on the much larger random motion, it creates a nonzero average velocity without aligning every electron's velocity. Thus the reason directly explains the assertion. The alternatives denying this link or treating either statement as false do not describe electron motion correctly.

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

Quick Tip to Solve: In drift questions, distinguish each electron's instantaneous velocity from the average velocity of all free electrons.

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

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

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

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

Solution:

Concept:

- Superposition of coherent light waves gives constructive interference in bright regions and destructive interference in dark regions.
- Interference and diffraction redistribute light energy in space; the total energy remains conserved.

Step 1: Evaluate the assertion The assertion is true. At dark fringes, wave amplitudes partially or completely cancel, reducing the local intensity. At bright fringes, amplitudes reinforce, producing a larger local intensity. Diffraction likewise produces an intensity pattern through superposition of contributions from different parts of the aperture.

Step 2: Evaluate the reason The reason is false. A reduction in intensity at one position does not imply destruction of energy. When the full pattern and all propagation directions are accounted for, energy missing from dark regions appears in brighter regions. The total outgoing energy equals the transmitted incident energy for an ideal lossless arrangement.

Step 3: Test whether the reason explains the assertion The assertion is explained by redistribution of energy through superposition, consistent with energy conservation. The reason instead denies conservation, so it cannot explain the assertion. Options requiring both statements to be true are excluded, and the assertion itself is not false.

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

Quick Tip to Solve: A dark fringe signals a local intensity minimum; compare the whole fringe pattern before deciding anything about energy conservation.

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

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

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

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

Solution:

Concept:

- The temperature coefficient describes the change of resistance with temperature: $\alpha = (1/R)(dR/dT)$.
- Conductivity depends on carrier density and mobility, not on whether the carriers have positive or negative charge.

Step 1: Evaluate the assertion In a metal, increasing temperature increases lattice vibrations and electron scattering, so resistance increases. In a semiconductor, thermal generation increases the number of charge carriers sufficiently to lower resistance. Thus the stated positive coefficient for metals and negative coefficient for a *p*-type semiconductor are correct in the usual CBSE treatment. Assertion (A) is true.

Step 2: Evaluate the reason Free electrons, which carry negative charge, conduct current in metals. Holes, which act as positive charge carriers, are the majority carriers in a *p*-type semiconductor. Reason (R) is therefore true.

Step 3: Test the explanatory link The sign of the carrier charge does not determine how resistance changes with temperature. The relevant effects are scattering in the metal and increasing carrier density in the semiconductor. Hence R does not explain A: option (A) gives an incorrect explanatory link, while (C) and (D) incorrectly classify true statements as false.

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

Quick Tip to Solve: For temperature-coefficient questions, track carrier density and scattering; never infer the coefficient from the sign of the carrier charge.

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

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

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

Solution:

Concept:

- Photoelectric emission requires the incident photon energy $h\nu$ to be at least the metal's work function ϕ .
- Photon energy is $E = hc/\lambda$; yellow light has less energy per photon than ultraviolet light.

Step 1: Evaluate the assertion Yellow light cannot eject photoelectrons from zinc because its photon energy is below zinc's threshold energy. Zinc requires sufficiently high-frequency radiation, typically ultraviolet, for photoelectric emission. Thus Assertion (A) is false.

Step 2: Evaluate the reason A yellow photon has energy about 2.1 eV, whereas the work function of zinc is about 4.3 eV. Consequently $h\nu < \phi$, contrary to the claim that yellow-photon energy exceeds the work function. Reason (R) is also false.

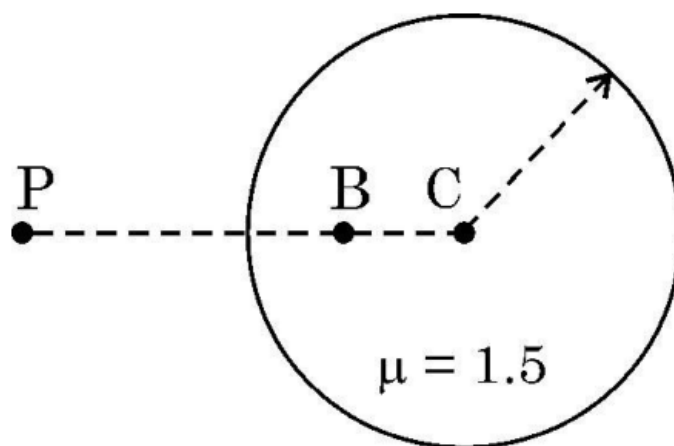
Step 3: Check the logical choice Since both statements are false, R cannot be a valid explanation of A. Options (A) and (B) require both statements to be true, and option (C) requires A to be true, so all three are excluded. Increasing yellow-light intensity cannot overcome the insufficient energy of each photon.

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

Quick Tip to Solve: Compare photon energy with the work function first; brighter light below the threshold frequency still cannot eject electrons.

Section B (10 marks)

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



Solution:

Concept:

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

Step 1: Assign the object distance and radius Let S be the left surface of the sphere, nearest the observer P. Light from B travels leftwards from glass into air. Since $CS = 40$ cm and $CB = 20$ cm, the bubble is $SB = 20$ cm behind S. Both B and C lie opposite the incident-light direction from S. Therefore

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

Step 2: Apply refraction at the near surface Substitute the signed distances into the spherical-refraction equation:

$$\begin{aligned} \frac{1}{v} - \frac{1.5}{-20} &= \frac{1 - 1.5}{-40}, \\ \frac{1}{v} + \frac{3}{40} &= \frac{1}{80}, \\ \frac{1}{v} &= -\frac{1}{16} \text{ cm}^{-1}. \end{aligned}$$

The negative sign means that the refracted rays appear to come from a point inside the glass. The apparent point is nearer the observed surface than the actual bubble, as expected for viewing glass from air.

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

Quick Tip to Solve: Measure the bubble's depth from the near surface, not from C; choose positive distances towards P before assigning the signs of both u and R .

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

Solution:

Concept:

- In normal adjustment, the objective's real image lies at the eyepiece's focal plane, so the final image is at infinity and the lens separation is $L = f_o + f_e$.
- The magnitude of the angular magnifying power is $|M| = f_o/f_e$, where f_o and f_e are the positive focal lengths of the objective and eyepiece.

Step 1: Write the two focal-length relations The given separation is 1.00 m. As both lenses are converging and the telescope is normally adjusted, their focal lengths add to this separation. The stated magnifying power 19 is its magnitude; inversion of the image does not make either focal length negative. Thus

$$f_o + f_e = 1.00 \text{ m}, \quad \frac{f_o}{f_e} = 19.$$

Step 2: Solve the simultaneous equations From the ratio, $f_o = 19f_e$. Substitute this in the separation relation:

$$\begin{aligned} 19f_e + f_e &= 1.00 \text{ m}, \\ f_e &= \frac{1.00}{20} \text{ m} = 0.050 \text{ m}, \\ f_o &= 19(0.050) \text{ m} = 0.950 \text{ m}. \end{aligned}$$

The computed focal lengths add to the stated lens separation, and their ratio is 19, satisfying both conditions.

Step 3: Conclusion The objective focal length is $f_o = 0.950 \text{ m} = 95 \text{ cm}$, and the eyepiece focal length is $f_e = 0.050 \text{ m} = 5 \text{ cm}$.

Quick Tip to Solve: For normal adjustment, obtain the shorter focal length directly from $f_e = L/(|M| + 1)$, then subtract it from L to find the objective focal length.

18. The ratio of de Broglie wavelengths of a proton and a deuteron accelerated by potential V_p and V_d respectively, $\left(\frac{\lambda_p}{\lambda_d}\right)$ is $\frac{1}{2}$. Find $\frac{V_p}{V_d}$. [2 marks]

Solution:

Concept:

- For a particle accelerated from rest through potential V, the kinetic energy gained is $K = qV$; in the non-relativistic regime, $p = \sqrt{2mqV}$.
- The de Broglie wavelength is $\lambda = h/p = h/\sqrt{2mqV}$. A proton and a deuteron both have charge $+e$, while $m_d \simeq 2m_p$.

Step 1: Form the wavelength ratio Apply the wavelength formula separately to the proton and the deuteron. The common factors h, 2 and e cancel when taking the ratio. The proton's mass and

potential appear in the denominator because wavelength is inversely proportional to momentum:

$$\frac{\lambda_p}{\lambda_d} = \sqrt{\frac{m_d V_d}{m_p V_p}} = \sqrt{\frac{2V_d}{V_p}}.$$

Step 2: Substitute the given ratio and square The wavelength ratio is $1/2$. Squaring removes the square root and gives

$$\frac{1}{4} = \frac{2V_d}{V_p},$$

$$V_p = 8V_d.$$

As a consistency check, this potential ratio makes $m_p V_p$ four times $m_d V_d$. The proton momentum is therefore twice the deuteron momentum, and its wavelength is half the deuteron wavelength, exactly as stated.

Step 3: Conclusion The required ratio of accelerating potentials is $\frac{V_p}{V_d} = 8$, or $V_p : V_d = 8 : 1$.

Quick Tip to Solve: For particles with equal charge, square the wavelength ratio before comparing mV; remember that the deuteron has twice the proton's mass.

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

Solution:

Concept:

- At normal incidence a ray travels undeviated, so its angle of refraction at the first face is zero.
- Inside a prism, the angles made with the two face normals satisfy $r_1 + r_2 = A$, where A is the prism angle. At an interface Snell's law is $n_1 \sin i = n_2 \sin r$.

Step 1: Find the internal angle of incidence An equilateral prism has apex angle $A = 60^\circ$. The ray is normally incident on the first face, hence $r_1 = 0^\circ$, even when the prism is immersed. Consequently, its angle of incidence on the adjacent face is

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

This angle is measured from the normal to the second face, not from the face itself.

Step 2: Apply Snell's law at the emergent face Let the absolute refractive index of the surrounding transparent medium be n_m . A ray grazing the surface has angle of refraction 90° with the normal. The angle 60° is therefore the critical angle for this glass-medium interface. Snell's law gives

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

Step 3: Conclusion The refractive index of the medium is $n_m = \frac{\sqrt{3}}{2}\mu$. It is smaller than the glass refractive index, consistent with emergence at the critical angle.

Quick Tip to Solve: Normal entry sets the first internal angle to zero; grazing emergence sets the external angle to 90° . Use the prism angle at the second face.

20. Find the temperature at which the resistance of a conductor increases by 25% of its value at 27°C . The temperature coefficient of resistance of the conductor is $2.0 \times 10^{-4}^\circ\text{C}^{-1}$. [2 marks]

Solution:

Concept:

- The linear temperature law is $R_T = R_{27}[1 + \alpha(T - 27^\circ\text{C})]$, taking the given initial temperature as the reference. Here α is the fractional increase in resistance per degree Celsius.
- An increase of 25% means $\Delta R/R_{27} = 25/100 = 0.25$; the new resistance is $1.25R_{27}$.

Step 1: Express the required fractional increase Let R_{27} be the resistance at 27°C and T the required final temperature. The stated increase is relative to R_{27} . Subtracting the initial resistance from the linear law and dividing by it gives

$$\frac{R_T - R_{27}}{R_{27}} = \alpha(T - 27^\circ\text{C}) = 0.25.$$

The unknown initial resistance cancels, so its numerical value is unnecessary.

Step 2: Calculate the rise and the final temperature Substitute $\alpha = 2.0 \times 10^{-4}^\circ\text{C}^{-1}$ to obtain the temperature rise:

$$\Delta T = \frac{0.25}{2.0 \times 10^{-4}} = 1250^\circ\text{C}.$$

This is a change in temperature, so add it to the initial temperature:

$$T = 27^\circ\text{C} + 1250^\circ\text{C}.$$

Step 3: Conclusion The required temperature is $T = 1277^\circ\text{C}$, using the given constant temperature coefficient and the linear resistance law.

Quick Tip to Solve: Divide the fractional increase 0.25 by α to get the temperature rise; then add 27°C to obtain the final temperature.

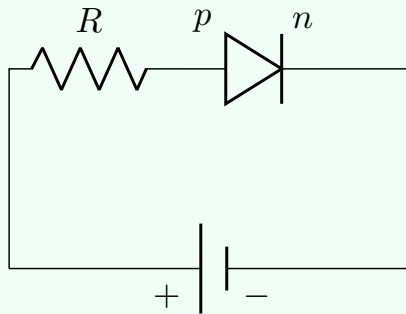
21. Draw the circuit diagram of a p - n junction diode in (i) forward biasing and (ii) reverse biasing. Also draw its I - V characteristics in the two cases. [2 marks]

Solution:

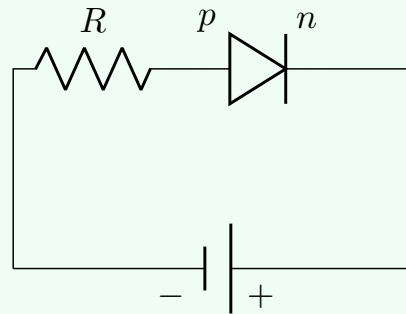
Concept:

- Forward bias connects the p side (anode) to the positive terminal and the n side (cathode) to the negative terminal, reducing the junction barrier.
- Reverse bias interchanges the supply polarity and increases the barrier. Forward current is mainly due to majority carriers; the small reverse saturation current is due to minority carriers.

Step 1: Draw the two biasing circuits In the circuits, the diode bar is its cathode, the n side. The resistor R limits current. In (i), p is connected to $+$ and n to $-$; in (ii), p is connected to $-$ and n to $+$. Thus reversing the battery reverses the bias without turning the diode around.



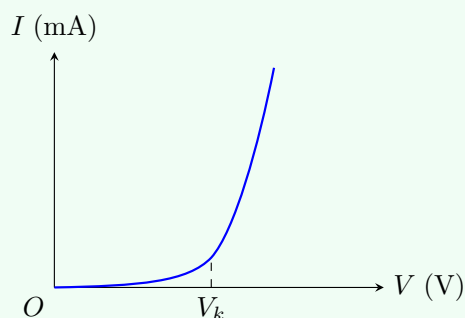
(i) Forward bias



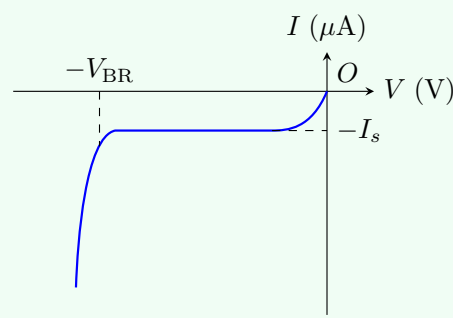
(ii) Reverse bias

(i) Forward bias and (ii) reverse bias; long battery plate is positive.

Step 2: Draw and interpret the characteristics With $V = V_p - V_n$, forward voltage and forward conventional current are positive. The forward current is small initially, then increases rapidly beyond the knee voltage V_k . Under reverse bias both signed voltage and current are negative; a small nearly constant reverse saturation current $-I_s$ flows until breakdown at $-V_{BR}$, beyond which its magnitude rises sharply. The reverse-current scale is much smaller than the forward-current scale, as indicated on the separate graphs.



Forward bias



Reverse bias

Forward and reverse characteristics (schematic; different current scales).

Step 3: Conclusion Forward bias is $p: +$, $n: -$ and gives a rapidly increasing current beyond the knee. Reverse bias is $p: -$, $n: +$ and gives only a small saturation current before breakdown, as shown.

Quick Tip to Solve: Identify the diode bar as n first. Then check whether the battery positive terminal reaches p (forward) or n (reverse).

Section C (21 marks)

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

(ii) Derive an expression for the mutual inductance of a system of two long coaxial solenoids of same length l , having turns N_1 and N_2 and of radii r_1, r_2 ($r_2 > r_1$). [3 marks]

Solution:

Concept:

- Mutual inductance M is the magnetic flux linkage with one coil per unit current in the other: $N_2\Phi_{21} = MI_1$. Equivalently, its induced emf is $\varepsilon_2 = -M dI_1/dt$.
- A long air-core solenoid of length l , turns N and current I produces $B = \mu_0 NI/l$ inside; the external field is negligible when end effects are neglected.

Step 1: Define mutual inductance and its unit Mutual inductance is the flux linkage of either coil due to unit current in the other coil, for fixed geometry and medium. Its SI unit is henry (H). Two coils have mutual inductance 1 H if a current changing at 1 A s^{-1} in one induces an emf of magnitude 1 V in the other:

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

Step 2: Find the flux due to the inner solenoid Let current I_1 flow in the inner solenoid of radius r_1 and N_1 turns. For the two long coaxial air-core solenoids of common length l , the field inside the inner solenoid is

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

Its field outside radius r_1 is negligible. Therefore only the common area $A_1 = \pi r_1^2$ contributes to the flux through each outer turn, although the outer radius is larger:

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

Step 3: Calculate the total linked flux Multiply the flux per outer turn by its N_2 turns, then compare with the definition:

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

$$M = \frac{N_2 \Phi_{21}}{I_1}.$$

Reversing the roles gives the same result: the outer solenoid's field is $\mu_0 N_2 I_2/l$, and each inner turn encloses area πr_1^2 . Thus the mutual inductance is reciprocal.

Step 4: Conclusion The mutual inductance is $M = \frac{\mu_0 N_1 N_2 \pi r_1^2}{l}$, measured in henry, assuming air or vacuum and negligible end effects. The smaller radius determines the shared flux area.

Quick Tip to Solve: For coaxial solenoids use the smaller cross-sectional area in $M = \mu_0 N_1 N_2 A/l$; do not use the larger area or add the two areas.

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

Solution:

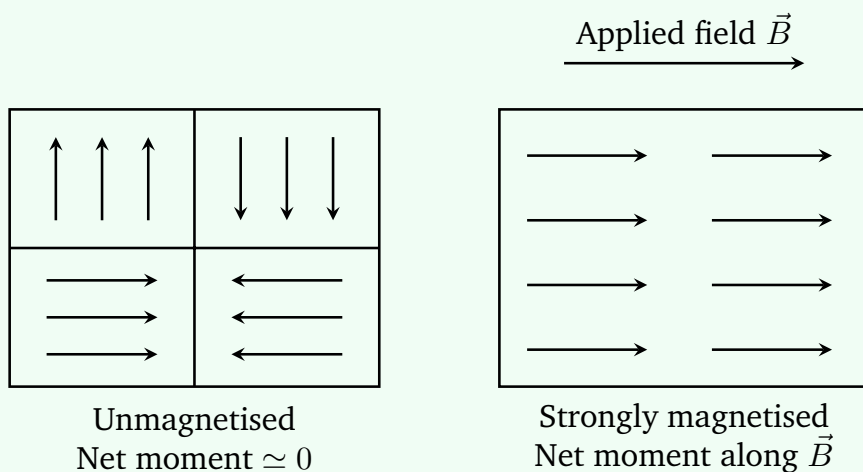
Concept:

- Ferromagnetism is the strong magnetisation of materials such as iron, cobalt and nickel in an applied magnetic field. Their magnetic susceptibility is large and positive.
- A magnetic domain is a small region in which many atomic magnetic moments are aligned parallel by their mutual interaction. Each domain therefore has a large spontaneous magnetic moment.

Step 1: Define ferromagnetic materials Ferromagnetic materials are strongly attracted by a magnet and become strongly magnetised along an applied field. Below their Curie temperature, they possess magnetic domains even with no external field.

Step 2: Explain the unmagnetised state Within each domain, atomic magnetic moments already point in the same direction. However, in an unmagnetised specimen, different domains point in different directions. Their vector contributions approximately cancel, so the specimen can have zero resultant magnetic moment although each individual domain is magnetised. The arrows in the left sketch represent atomic moments; the dividing lines represent domain boundaries.

Step 3: Explain magnetisation by an applied field When an external magnetic field is applied, domains favourably oriented along the field grow at the expense of less favourably oriented domains through motion of domain boundaries. The magnetisation of domains can also rotate towards the field. Thus a large resultant magnetic moment develops along the field. In a sufficiently strong field, nearly all moments align, approaching magnetic saturation, as shown schematically on the right. On removing the field, some alignment may persist, giving remanent magnetisation.



Domain model: unmagnetised specimen and an idealised nearly saturated state.

Step 4: Conclusion Ferromagnetic materials become strongly magnetised because an applied field changes domain sizes and directions, producing a large net moment along the field.

Quick Tip to Solve: Draw parallel arrows within each domain, but different domain directions before magnetisation; show predominantly field-aligned arrows after magnetisation.

23. Two conducting spherical shells A and B of radii R and $2R$ are kept far apart and charged to the same charge density σ . They are connected by a wire. Obtain an expression for final potential of shell A . [3 marks]

Solution:

Concept:

- The charge on a spherical shell of radius r and surface charge density σ is $Q = 4\pi r^2 \sigma$.
- For an isolated conducting sphere, its surface potential relative to infinity is $V = Q/(4\pi\epsilon_0 r)$, where ϵ_0 is the permittivity of free space. The shells are far apart, so their mutual potential contributions are neglected.
- When conductors are connected by a wire, charge redistributes until their potentials are equal. Their total charge is conserved; the wire's capacitance is taken to be negligible.

Step 1: Calculate the initial charges Equal initial surface charge densities do not imply equal charges because the shell areas differ. Using radii R and $2R$, respectively,

$$\begin{aligned} Q_A &= 4\pi R^2 \sigma, \\ Q_B &= 4\pi (2R)^2 \sigma = 16\pi R^2 \sigma, \\ Q_{\text{total}} &= Q_A + Q_B = 20\pi R^2 \sigma. \end{aligned}$$

Their initial potentials are $\sigma R/\epsilon_0$ and $2\sigma R/\epsilon_0$, so they are initially at different potentials.

Step 2: Apply the equilibrium condition Let the final charges be q_A and q_B . The connecting wire makes the two shells equipotential. Hence,

$$\frac{q_A}{4\pi\epsilon_0 R} = \frac{q_B}{4\pi\epsilon_0 (2R)} \Rightarrow q_B = 2q_A.$$

Thus the final charges divide in the ratio of the radii, rather than in the ratio of their surface areas.

Step 3: Use conservation of charge No charge is supplied to or removed from the connected system, so

$$\begin{aligned} q_A + q_B &= 20\pi R^2 \sigma, \\ 3q_A &= 20\pi R^2 \sigma, \\ q_A &= \frac{20\pi R^2 \sigma}{3}. \end{aligned}$$

Substitute this charge into $V_A = q_A/(4\pi\epsilon_0 R)$ to obtain the common final potential, with zero potential defined at infinity.

Step 4: Conclusion The final potential of shell A , equal to that of shell B , is

$$V_A = \frac{1}{4\pi\epsilon_0 R} \frac{20\pi R^2 \sigma}{3} = \frac{5\sigma R}{3\epsilon_0}.$$

For positive σ , this lies between the two initial potentials, as expected.

Quick Tip to Solve: For distant spheres joined by a wire, use $V_f = Q_{\text{total}}/[4\pi\epsilon_0(R_A + R_B)]$; first calculate each initial charge from its surface area.

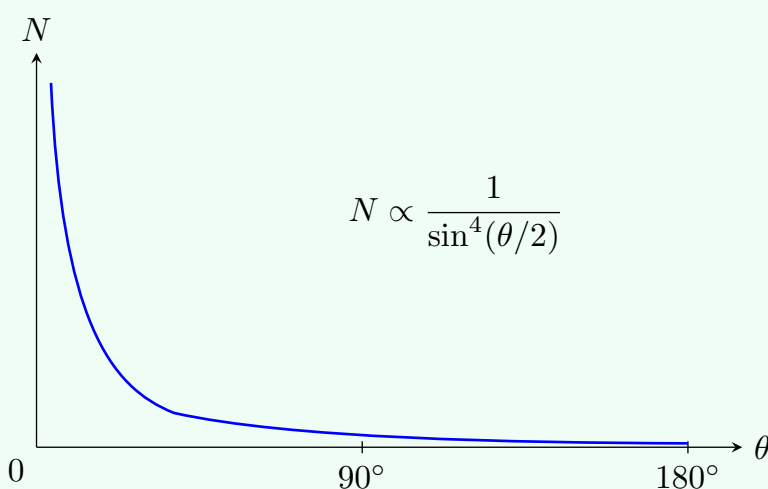
24. Draw the graph showing variation of scattered particles detected (N) with the scattering angle (θ) in Geiger-Marsden experiment. Write two conclusions that you can draw from this graph. Obtain the expression for the distance of closest approach in this experiment. [3 marks]

Solution:

Concept:

- In Rutherford scattering, the number N of alpha particles detected in equal solid angles varies as $N \propto 1/\sin^4(\theta/2)$, where θ is the scattering angle.
- For a head-on approach, the initial kinetic energy K of an alpha particle of charge $+2e$ is converted into electrostatic potential energy in the field of a nucleus of charge $+Ze$.

Step 1: Sketch the angular distribution The count is very large at small scattering angles and decreases rapidly as the angle increases. Only a very small, but nonzero, number of alpha particles are detected near 180° . The sketch shows this trend schematically; its vertical scale is arbitrary. The ideal scattering expression is not evaluated at exactly $\theta = 0$, where the forward, unscattered beam lies.



Schematic angular distribution of scattered alpha particles (arbitrary vertical scale).

Step 2: Infer the structure of the atom First, the predominance of particles with negligible or small deflections shows that most of the atom is empty space. Second, the very small fraction scattered through large angles, including backward directions, shows that the repulsive positive charge and almost the entire atomic mass are concentrated in a tiny, dense nucleus. Such large deflections cannot be explained by positive charge spread uniformly over the atom.

Step 3: Apply energy conservation to a head-on collision Take the electrostatic potential energy to be zero far from the nucleus. At the closest approach r_0 in a head-on encounter, the alpha particle momentarily stops, so its kinetic energy becomes zero. Neglecting nuclear recoil, conservation of energy gives

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

Rearranging,

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

Here m and v are the alpha particle's mass and initial speed, and Z is the atomic number of the target nucleus. This expression refers specifically to head-on motion, with zero initial angular momentum.

Step 4: Conclusion The count falls sharply with scattering angle: the atom is mostly empty space with a small, dense, positively charged nucleus. The head-on distance of closest approach is $r_0 =$

$$2Ze^2/(4\pi\epsilon_0 K).$$

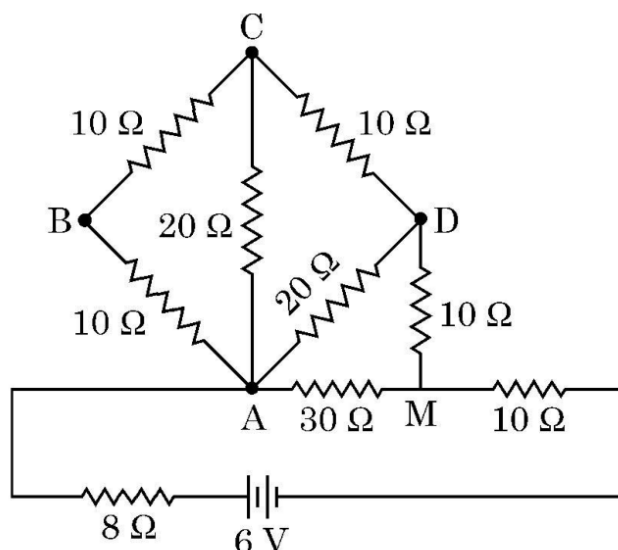
Quick Tip to Solve: For closest approach, set the incident kinetic energy equal to the Coulomb energy and use the alpha particle's charge as $2e$, not e .

25. In the given network, calculate:

(i) effective resistance between points A and M, and

(ii) power supplied by the battery.

[3 marks]



Solution:

Concept:

- Resistances in series add: $R_s = R_1 + R_2$. For two resistances in parallel, $R_p = R_1 R_2 / (R_1 + R_2)$.
- Ohm's law gives the battery current $I = V/R_{\text{total}}$; the power supplied by an ideal battery of voltage V is $P = VI = V^2/R_{\text{total}}$.

Step 1: Reduce the branches between A and C Point B joins only the two 10Ω resistors AB and BC, so these are in series. Their combined resistance is 20Ω . This path from A through B to C is in parallel with the direct 20Ω resistor AC:

$$R_{ABC} = 10 + 10 = 20\Omega, \quad R_{AC} = \frac{20 \times 20}{20 + 20} = 10\Omega.$$

The two paths have the same endpoints A and C, which is the reason for using the parallel rule.

Step 2: Reduce the network from A to M After that replacement, the equivalent AC resistor is in series with the 10Ω resistor CD, making the ACD path 20Ω . This path is in parallel with the direct 20Ω resistor AD. Thus,

$$R_{AD} = \frac{(10 + 10) \times 20}{(10 + 10) + 20} = 10\Omega.$$

This equivalent AD resistor is in series with the 10Ω resistor DM. The resulting 20Ω path from A to M is in parallel with the direct 30Ω resistor AM:

$$R_{AM} = \frac{(10 + 10) \times 30}{(10 + 10) + 30} = \frac{600}{50} = 12\Omega.$$

This is the effective resistance of the passive network between the specified points, before adding the external battery-branch resistors.

Step 3: Calculate battery current and power The external 8Ω resistor and the 10Ω resistor to the right of M are in series with the equivalent AM network. The battery therefore sees

$$R_{\text{total}} = 8 + 12 + 10 = 30\Omega.$$

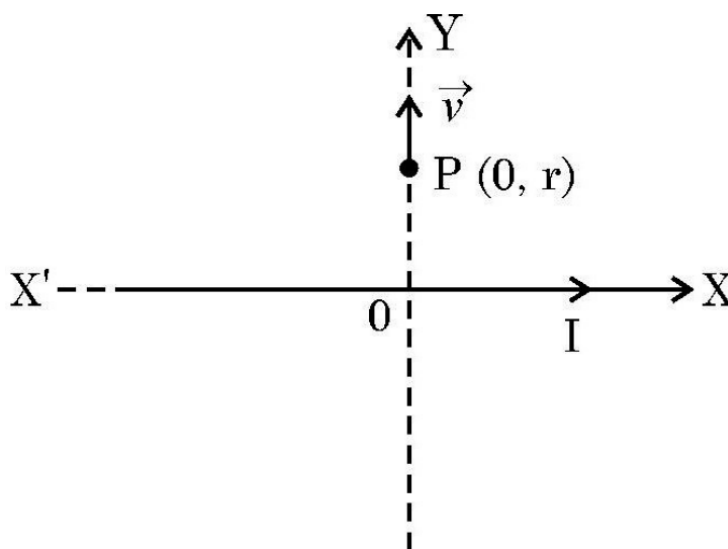
With the printed battery voltage $V = 6\text{ V}$,

$$I = \frac{6}{30} = 0.20\text{ A}, \quad P = VI = 6 \times 0.20 = 1.20\text{ W}.$$

Step 4: Conclusion (i) The effective resistance between A and M is 12Ω . (ii) The battery supplies 1.20 W , with a total current of 0.20 A .

Quick Tip to Solve: Start with the two resistors meeting at B and reduce inwards; add the external 8Ω and 10Ω only when calculating battery current.

26. An infinite straight conductor is kept along $X'X$ axis and carries a current I . A charge q at point $P(0, r)$ starts moving with velocity $\vec{v} = v_0\hat{j}$ as shown in figure. Find the direction and magnitude of force initially experienced by the charge. [3 marks]



Solution:

Concept:

- The magnetic field at perpendicular distance r from an infinite straight conductor carrying current I has magnitude $B = \mu_0 I / (2\pi r)$; its direction follows the right-hand thumb rule.
- A charge q moving with velocity $\vec{v}$ in a magnetic field experiences $\vec{F} = q(\vec{v} \times \vec{B})$, of magnitude $|q|vB \sin \phi$, where ϕ is the angle between velocity and field.

Step 1: Determine the magnetic field at P In the figure the current flows along the positive X direction, so its direction is $+\hat{i}$. Point $P(0, r)$ is above the wire, on the positive Y axis. Curling the fingers of the right hand around the wire with the thumb along the current shows that the field at P points out of

the page. Taking this outward direction as $+\hat{k}$,

$$\vec{B}(P) = \frac{\mu_0 I}{2\pi r} \hat{k}.$$

The distance used here is the perpendicular distance r , rather than a distance measured along the wire.

Step 2: Evaluate the vector magnetic force The initial velocity is $\vec{v} = v_0 \hat{j}$. It is perpendicular to the field, so $\sin \phi = 1$. Substituting into the magnetic-force law and using $\hat{j} \times \hat{k} = \hat{i}$,

$$\begin{aligned}\vec{F} &= q(v_0 \hat{j}) \times \left(\frac{\mu_0 I}{2\pi r} \hat{k} \right) \\ &= \frac{\mu_0 I q v_0}{2\pi r} \hat{i}.\end{aligned}$$

For a positive charge, the initial force is along positive X, parallel to the current. If q is negative, the force is along negative X. The force is perpendicular to the instantaneous velocity; thus it initially changes the direction of motion, without doing magnetic work on the particle.

Step 3: Conclusion Initially, $\vec{F} = \mu_0 I q v_0 \hat{i} / (2\pi r)$, with magnitude $F = \mu_0 I |q| v_0 / (2\pi r)$. Its direction is $+X$ for a positive charge and $-X$ for a negative charge.

Quick Tip to Solve: Find the wire's field first: here it is out of the page. Then apply $\hat{j} \times \hat{k} = \hat{i}$, reversing the result only for a negative charge.

27. Explain the following giving reasons:

- (i) 'Electromagnetic waves differ considerably in their mode of interaction with matter'.
- (ii) 'Food items to be heated in microwave oven must contain water'.
- (iii) 'Welders wear face mask with glasses during welding'.

[3 marks]

Solution:

Concept:

- Electromagnetic radiation transfers energy to matter. Its photon energy is $E = h\nu$, where h is Planck's constant and ν is frequency; different frequencies therefore excite different processes in matter.
- Water molecules possess permanent electric dipole moments and absorb microwave energy. Ultra-violet radiation can damage living tissue, particularly the eyes.

Step 1: (i) Relate interaction to frequency Electromagnetic waves span a very wide range of frequencies and hence photon energies. Matter absorbs radiation according to its molecular, atomic and nuclear energy levels, so different regions of the spectrum produce different effects. For example, microwaves cause polar molecules to respond to an alternating electric field, infrared radiation excites molecular vibrations and produces heating, and sufficiently energetic ultraviolet or X-ray radiation can excite or ionise atoms. Thus a common electromagnetic nature does not imply the same mode of interaction with matter.

Step 2: (ii) Explain the role of water in heating food In a microwave oven, the rapidly changing electric field acts on the electric dipoles of water molecules. The molecules repeatedly try to align with the changing field and absorb microwave energy. Intermolecular interactions transfer this energy

into random molecular motion, increasing the temperature of the water and the surrounding food. Hence water in the food provides an effective means of absorbing the microwaves and distributing their energy as heat.

Step 3: (iii) Explain the protective welding mask The welding arc emits intense visible light and ultraviolet radiation. Ultraviolet radiation can damage the eyes, and exposure can also injure facial skin. The protective face mask shields the face, while its suitable filter glasses absorb harmful ultraviolet radiation and reduce the intense visible light reaching the eyes.

Step 4: Conclusion The different frequencies and photon energies explain the different interactions; water absorbs microwave energy and heats the food; the welding mask and filter glasses protect the face and eyes from harmful radiation.

Quick Tip to Solve: Link each use to the relevant interaction: photon energy for the spectrum, polar water molecules for microwave heating, and ultraviolet absorption for welding protection.

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

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

Solution:

Concept:

- Nuclear fission splits a heavy nucleus into lighter nuclei; nuclear fusion combines light nuclei into a heavier nucleus. Energy is released when the products have greater binding energy per nucleon, with mass defect converted into energy according to $E = \Delta mc^2$.
- The number of nuclei in a pure sample is $N = (m/M)N_A$, where m is its mass, M its molar mass and $N_A = 6.023 \times 10^{23} \text{ mol}^{-1}$. Total fission energy is N times the energy per fission.

Step 1: (a) Distinguish fission from fusion In fission, one heavy nucleus, such as uranium or plutonium, breaks into two medium-mass nuclei, usually after absorbing a neutron. Additional neutrons and energy are released; the neutrons can cause further fissions and sustain a chain reaction. In fusion, two light nuclei combine to form a heavier nucleus, releasing energy. Fusion requires very high temperature and sufficient confinement so that the positively charged nuclei can overcome their electrostatic repulsion and approach within the range of the nuclear force. Thus fission starts with a heavy nucleus and splits it, whereas fusion starts with light nuclei and joins them.

Step 2: (b) Calculate the number of plutonium nuclei Approximate the molar mass of pure ${}^{239}_{94}\text{Pu}$ as 239 g mol⁻¹. The sample mass is 1 g, so the number of nuclei available to undergo fission is

$$N = \frac{1 \text{ g}}{239 \text{ g mol}^{-1}} \times 6.023 \times 10^{23} \text{ mol}^{-1} = 2.52 \times 10^{21}.$$

Each atom supplies one plutonium nucleus, and the question specifies that every such nucleus undergoes fission.

Step 3: Multiply by the energy of each fission Each fission releases an average of 180 MeV. Therefore the total energy, kept in the requested unit, is

$$E = N \times 180 \text{ MeV} = (2.52 \times 10^{21}) \times 180 \text{ MeV} = 4.54 \times 10^{23} \text{ MeV}.$$

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

Quick Tip to Solve: Convert the sample mass into a number of nuclei using 239 g per mole, then multiply by 180 MeV; no joule conversion is needed here.

Section D (8 marks)

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

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

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

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

Correct Answer: (B) 0.01 eV

Solution:

Concept:

- A pentavalent impurity is a donor: four valence electrons form bonds in the germanium lattice, while the fifth is weakly bound.
- A donor level lies just below the conduction band. The donor ionisation energy is much smaller than the intrinsic semiconductor band gap.

Step 1: Identify the donor ionisation energy Only a small energy is needed to release the fifth electron into the conduction band. For a pentavalent donor in germanium, this energy is approximately 0.01 eV, which can be supplied by thermal energy at ordinary temperatures.

Step 2: Compare all the printed choices The value 0.001 eV in (A) is below the standard approximate donor energy in Ge. The values 0.72 eV and 1.1 eV in (C) and (D) are on the scale of the intrinsic band gaps of Ge and Si, respectively; they are not the energy needed to ionise the weakly bound donor electron.

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

Quick Tip to Solve: Distinguish the tiny donor-to-conduction-band energy in Ge, about 0.01 eV, from the much larger intrinsic band gap.

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

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

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

Solution:

Concept:

- At thermal equilibrium and a fixed temperature, the mass action law is $n_e n_h = n_i^2$, where n_e , n_h and n_i are the electron, hole and intrinsic carrier number densities.
- A density of 1 cm^{-3} equals 10^6 m^{-3} , since one cubic metre contains 10^6 cubic centimetres.

Step 1: Apply the mass action law Using the printed values $n_i = 2.0 \times 10^{10} \text{ cm}^{-3}$ and $n_h = 8 \times 10^3 \text{ cm}^{-3}$,

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

Step 2: Convert into the units of the options Multiply the density per cubic centimetre by 10^6 to express it per cubic metre:

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

Options (A), (B) and (C) have different densities and do not satisfy the mass action law with the given hole density. Pentavalent doping also correctly gives electrons as the majority carriers.

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

Quick Tip to Solve: Square the intrinsic density before dividing by the hole density, then multiply by 10^6 when converting from per cubic centimetre to per cubic metre.

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

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

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

Solution:

Concept:

- Diffusion is the movement of particles from a region of higher concentration to a region of lower concentration.
- Electrons are the majority carriers in an n -type region; holes are the majority carriers in a p -type region.

Step 1: Follow the electron concentration gradient The electron concentration is much greater on the n -side than on the p -side. Therefore electrons diffuse from the n -region into the p -region when the junction begins to form.

Step 2: Follow the hole concentration gradient The hole concentration is much greater on the p -side than on the n -side. Holes therefore diffuse from the p -region into the n -region. Option (A) reverses both diffusion directions; (B) reverses the hole direction and (D) reverses the electron direction. Only (C) gives both concentration-driven motions correctly.

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

Quick Tip to Solve: For diffusion, start each carrier on the side where it is the majority carrier; electrons start at n and holes at p .

OR

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

[1 mark]

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

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

Solution:

Concept:

- Diffusion current is driven by the large concentration gradients of majority carriers across a newly formed p - n junction.
- Drift current is driven by the electric field of the depletion region, which develops as diffusion leaves behind fixed ionised donors and acceptors.

Step 1: Examine the junction at the start Initially, electrons and holes have large concentration differences across the junction. Majority carriers therefore diffuse strongly across it, giving a large diffusion current. The depletion layer and its barrier field have only begun to develop, so the opposing drift current is initially small.

Step 2: Distinguish the initial stage from equilibrium As the depletion region forms, its field opposes further majority-carrier diffusion and promotes drift. Eventually the two opposing currents balance at equilibrium. The question asks about the initial stage: (B) reverses the current sizes, (C) incorrectly makes the initial drift current large, and (D) incorrectly makes the initial diffusion current small.

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

Quick Tip to Solve: The word initially points to a large concentration gradient but a barrier field that is still developing.

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

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

Correct Answer: (D) 50 Hz, 100 Hz

Solution:

Concept:

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

Step 1: Calculate the input frequency Comparing the given voltage with the standard sinusoidal form gives $\omega = 100\pi \text{ rad s}^{-1}$.

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

The amplitude 0.5 V does not enter the frequency calculation.

Step 2: Count the output pulses Half-wave rectification removes one half-cycle but leaves successive pulses one full input period apart. Full-wave rectification reverses one half-cycle, giving pulses half an input period apart. Thus the respective frequencies are 50 Hz and 100 Hz. Options (A) and (B) incorrectly halve the input frequency for the half-wave output, while (C) misses the frequency doubling in full-wave rectification.

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

Quick Tip to Solve: First divide the coefficient of t by 2π ; then use one pulse per cycle for half-wave and two for full-wave rectification.

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

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

(A) $-\frac{5}{6}$ D

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

(C) $\frac{4}{3}$ D

(D) $\frac{3}{2}$ D

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

Solution:

Concept:

- Lens power is $P = 1/f$ in dioptres when focal length f is in metres. A converging lens has positive power and a diverging lens negative power.
- For thin lenses in contact, individual powers add algebraically: $P = P_1 + P_2$.

Step 1: Assign the signed focal lengths The converging lens has $f_1 = +0.20$ m, whereas the diverging lens has $f_2 = -0.15$ m. Hence,

$$P_1 = +5 \text{ D}, \quad P_2 = -\frac{20}{3} \text{ D}.$$

Step 2: Add the powers The lenses are in contact, so no separation correction is needed:

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

The diverging lens has the larger power magnitude and therefore determines the negative sign. Options (C) and (D) have the wrong sign; option (A), $-5/6$ D, has the wrong magnitude. Focal lengths themselves must not be added.

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

Quick Tip to Solve: Convert centimetres to metres and give the diverging focal length a minus sign before adding reciprocal focal lengths.

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

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

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

Solution:

Concept:

- For a thin lens in air, the lens maker's formula is $1/f = (\mu - 1)(1/R_1 - 1/R_2)$, where μ is the material's refractive index.
- For a biconvex lens with light travelling left to right, the first radius is positive and the second negative under the Cartesian sign convention.

Step 1: Apply the radius signs Choose $R_1 = +R$ and $R_2 = -2R$. The given radii are magnitudes, so using both as positive would be incorrect. Their curvature contribution is

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

Interchanging the two surfaces gives the same sum and hence the same focal length.

Step 2: Substitute the printed focal length The official paper gives $f = 4R/3$. Therefore,

$$\frac{3}{4R} = (\mu - 1) \frac{3}{2R} \Rightarrow \mu - 1 = \frac{1}{2}.$$

Options (A), (B) and (D) would give $\mu - 1 = 2/3, 1/3, 2/5$, respectively, and none satisfies this equation.

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

Quick Tip to Solve: Treat R and $2R$ as radius magnitudes: opposite signs make their reciprocal curvatures add for a biconvex lens.

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

[1 mark]

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

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

Solution:

Concept:

- An equiconvex thin lens has $1/f = 2(\mu_{\text{rel}} - 1)/R$, where R is the radius magnitude and $\mu_{\text{rel}} = n_{\text{lens}}/n_{\text{medium}}$.
- Under normal dispersion, the refractive index of glass increases as the wavelength decreases; lens power therefore increases for shorter wavelengths.

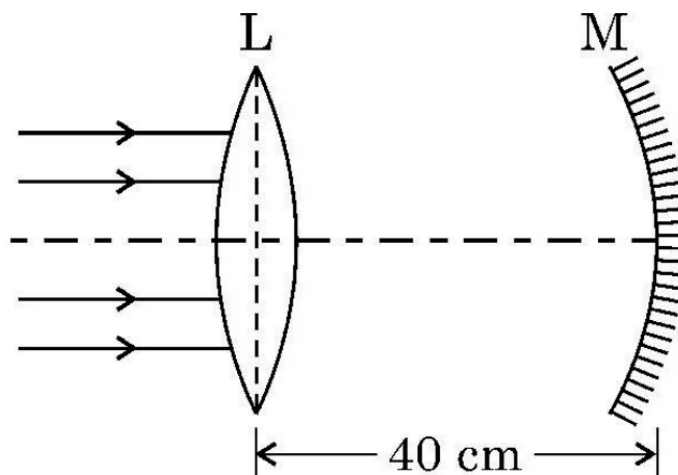
Step 1: Compare immersion and wavelength changes Dipping an ordinary glass lens in water reduces its refractive index relative to the surrounding medium. Thus $\mu_{\text{rel}} - 1$ and the converging power decrease, while the focal length increases, as stated in (A). Decreasing the wavelength increases the material's refractive index and power, so the focal length decreases; (B) reverses this trend.

Step 2: Check curvature and cutting effects At fixed refractive index, $f = R/[2(\mu_{\text{rel}} - 1)]$, so a decrease in R decreases f , contrary to (C). Cutting the lens into two parts along its principal axis reduces the aperture but preserves both surface curvatures. Each part retains the original focal length, so (D) is also false.

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

Quick Tip to Solve: Use the refractive index relative to the surrounding medium; a cut along the principal axis changes aperture, not focal length.

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



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

Correct Answer: No listed option gives the final image after the complete return path: it is at infinity. Option (B) gives the intermediate image formed by the mirror.

Solution:

Concept:

- A convex lens focuses an incident parallel beam at its principal focus; light from its focus emerges parallel on passing through it.
- A concave mirror forms a real image at its centre of curvature for an object at that centre. Its radius of curvature is $2f_M$.

Step 1: Locate the image made on the first lens passage Set the lens at $x = 0$ and the mirror at $x = 40$ cm, with positive x to the right. The incident parallel beam converges at the lens focus $x = 10$ cm, then diverges toward the mirror. This point is $40 - 10 = 30$ cm in front of the mirror.

Step 2: Find the image formed by the mirror Since $2f_M = 30$ cm, the mirror's object is at its centre of curvature. Reflection brings the rays back to the same point, $x = 10$ cm. This intermediate real image is 10 cm to the right of the lens and corresponds to option (B). None of the other finite locations listed is the mirror's image.

Step 3: Follow the reflected rays through the lens again After crossing that point, the rays continue leftward toward the lens. Their object is now at the right-hand focus of the lens, so they emerge parallel to the left. With distances measured along this returning direction, $u = -10$ cm and $f = +10$ cm:

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

Thus the complete optical system has its final image at infinity, which is absent from the printed choices.

Step 4: Conclusion As worded, no option describes the final image after the return through the lens:

it is at infinity. If the question intends only the mirror's intermediate image, the corresponding option is (B), 10 cm right of the lens.

Quick Tip to Solve: In a lens-mirror system, trace the return through the lens as well; here the mirror sends rays back through the lens's focal point.

OR

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

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

Correct Answer: (A) real, 24 cm

Solution:

Concept:

- A parallel incident beam forms a real image at the image-side focus of a convex lens. That image acts as the object for the next lens.
- For a thin lens, $1/v - 1/u = 1/f$, with signed object distance u , image distance v , and focal length f .

Step 1: Locate the object for the second lens Lens L_1 brings the parallel beam to a focus 16 cm to its right. Lens L_2 lies 40 cm to the right of L_1 , so this point lies $40 - 16 = 24$ cm to the left of L_2 . The rays diverge from it before reaching L_2 , giving a real object with $u_2 = -24$ cm.

Step 2: Apply the lens formula to the second lens With $f_2 = +12$ cm,

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

The positive image distance means a real image on the outgoing side of L_2 . Options (B) and (D) incorrectly call the image virtual, while (C) gives a distance that does not satisfy the lens formula. Since the object is at $2f_2$, its image must also be at $2f_2$.

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

Quick Tip to Solve: Subtract the first focal length from the lens separation: $40 - 16 = 24 = 2f_2$, so the second image is immediately located at $2f_2$.

Section E (15 marks)

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

(ii) Two capacitors of different capacitances are connected first (1) in series and then (2) in parallel across a dc source of 100 V. If the total energy stored in the combination in the two cases are 40 mJ and 250 mJ respectively, find the capacitance of the capacitors. [5 marks]

Solution:

Concept:

- Capacitance is $C = Q/V$, where Q is the magnitude of charge on either plate and V is the potential difference between the plates.
- For free surface charge density $\sigma = Q/A$, the electric fields in air and a dielectric of relative permittivity K are $E_0 = \sigma/\epsilon_0$ and $E_K = \sigma/(K\epsilon_0)$, neglecting edge effects.
- The energy stored across a fixed voltage is $U = \frac{1}{2}C_{\text{eq}}V^2$. For two capacitors, $C_s = C_1C_2/(C_1 + C_2)$ in series and $C_p = C_1 + C_2$ in parallel.

Step 1: (i) Divide the space into air and dielectric regions Let the slab fill the plate area A , with its faces parallel to the plates. The dielectric thickness is t , and the total remaining air thickness is $d - t$. If the plate charges are $+Q$ and $-Q$, the fields normal to the plates are

$$E_0 = \frac{Q}{\epsilon_0 A}, \quad E_K = \frac{Q}{K\epsilon_0 A}.$$

Polarisation reduces the field inside the slab. The potential drops across the air and dielectric regions add because these regions lie successively along a field line.

Step 2: (i) Add the potential drops and obtain the capacitance The position of the slab within the gap does not matter; only the total air thickness enters. Hence

$$\begin{aligned} V &= E_0(d - t) + E_K t \\ &= \frac{Q}{\epsilon_0 A} \left(d - t + \frac{t}{K} \right), \\ C &= \frac{Q}{V} = \frac{\epsilon_0 A}{d - t + t/K}. \end{aligned}$$

As checks, $t = 0$ gives $\epsilon_0 A/d$, while $t = d$ gives $K\epsilon_0 A/d$, the fully filled capacitor result.

Step 3: (ii) Convert the two energies into equivalent capacitances In each connection the equivalent capacitor is across the same 100 V supply. Use $C_{\text{eq}} = 2U/V^2$, converting millijoules to joules:

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

The larger energy corresponds to the larger equivalent capacitance, as expected for the parallel connection.

Step 4: (ii) Solve for the individual capacitances Expressing C_1 and C_2 numerically in microfarads,

the sum is $C_1 + C_2 = 50$, while the product follows from the series result:

$$C_1 C_2 = C_s (C_1 + C_2) = 8 \times 50 = 400.$$

Each capacitance is therefore a root of

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

Substitution checks both connections: $10 + 40 = 50$ and $10 \times 40 / (10 + 40) = 8$, in microfarads. Interchanging the capacitor names does not change either result.

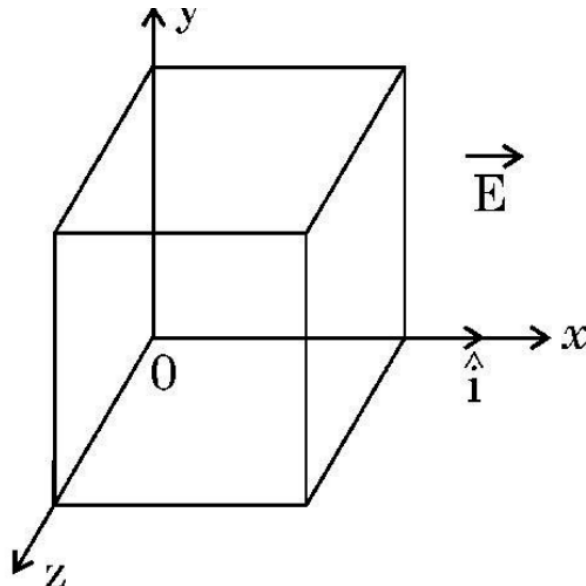
Step 5: Conclusion (i) $C = \frac{\epsilon_0 A}{d - t + t/K}$. (ii) The two capacitances are $10 \mu\text{F}$ and $40 \mu\text{F}$.

Quick Tip to Solve: At the same supply voltage, first turn each stored energy into an equivalent capacitance using $2U/V^2$; then use the parallel sum and series product to form a quadratic.

OR

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

(ii) Electric field $\vec{E}$ in a region is given by $\vec{E} = (5x^2 + 2)\hat{i}$, where E is in N/C and x is in meters. A cube of side 10 cm is placed in the region as shown in figure. Calculate (1) the electric flux through the cube, and (2) the net charge enclosed by the cube. [5 marks]



Solution:

Concept:

- Gauss's law states $\oint \vec{E} \cdot d\vec{A} = Q_{\text{enc}}/\epsilon_0$, where $d\vec{A}$ points outward from the closed surface.
- By symmetry, the field of a uniformly charged infinite plane sheet is perpendicular to the sheet and has equal magnitude at equal distances on its two sides. Surface charge density is $\sigma = Q/A$.
- For a field $\vec{E} = E(x)\hat{i}$, only faces with an outward normal along $+\hat{i}$ or $-\hat{i}$ contribute flux through a cube aligned with the coordinate axes.

Step 1: (i) Choose a Gaussian pillbox across the sheet Consider an imaginary short cylinder whose axis is perpendicular to the infinite sheet, with one flat face on each side. Let each flat face have area S . Translational symmetry along the sheet rules out a tangential field, and reflection symmetry makes the normal field magnitudes on the two sides equal. For a positively charged sheet the field points away from the sheet on both sides. The curved surface contributes no flux because its area vectors are parallel to the sheet, whereas the field is normal to it. The field is uniform over each flat face, and the outward area vector there is along the field, so each contributes ES .

Step 2: (i) Apply Gauss's law to obtain the sheet field The charge inside the pillbox is the charge on the intercepted sheet area, $Q_{\text{enc}} = \sigma S$. Consequently,

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

With $\hat{n}$ the unit normal pointing from the sheet toward the observation side, the vector result is

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

A negative σ reverses the direction toward the sheet. The result is independent of distance because the sheet is idealised as infinite.

Step 3: (ii)(1) Identify the contributing cube faces The figure places the left face at $x = 0$ and the right face at $x = a$, where $a = 10 \text{ cm} = 0.10 \text{ m}$. Both faces have area $a^2 = 0.010 \text{ m}^2$. For the given field,

$$E(0) = 2 \text{ N/C}, \quad E(a) = 5(0.10)^2 + 2 = 2.05 \text{ N/C}.$$

The four remaining faces have normals along the y or z direction. Their flux is zero because the electric field is everywhere along $+x$.

Step 4: (ii)(1) Add the outward fluxes with their signs On the left face the outward normal is $-\hat{i}$, giving negative flux; on the right face it is $+\hat{i}$, giving positive flux. Therefore the closed-surface flux is

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

The constant 2 N/C part of the field enters and leaves equally and cancels. The positive flux arises from the increase in field strength across the cube.

Step 5: (ii)(2) Calculate the enclosed charge Gauss's law relates the net flux to the algebraic enclosed charge:

$$\begin{aligned}Q_{\text{enc}} &= \varepsilon_0 \Phi_E \\&= (8.854 \times 10^{-12})(5.0 \times 10^{-4}) \\&= 4.427 \times 10^{-15} \text{ C.}\end{aligned}$$

The enclosed charge is positive, consistent with more field emerging from the right face than entering through the left face.

Step 6: Conclusion (i) $\vec{E} = \frac{\sigma}{2\varepsilon_0} \hat{n}$. (ii) The net outward flux is $5.0 \times 10^{-4} \text{ N m}^2/\text{C}$, and the enclosed charge is $+4.43 \times 10^{-15} \text{ C}$.

Quick Tip to Solve: For this cube, subtract the fields at the two x-faces before multiplying by the face area; the constant field term cancels, and the other four faces contribute zero.

32(a). (i) Draw a ray diagram for the formation of the image of an object by a convex mirror. Hence, obtain the mirror equation.

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

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

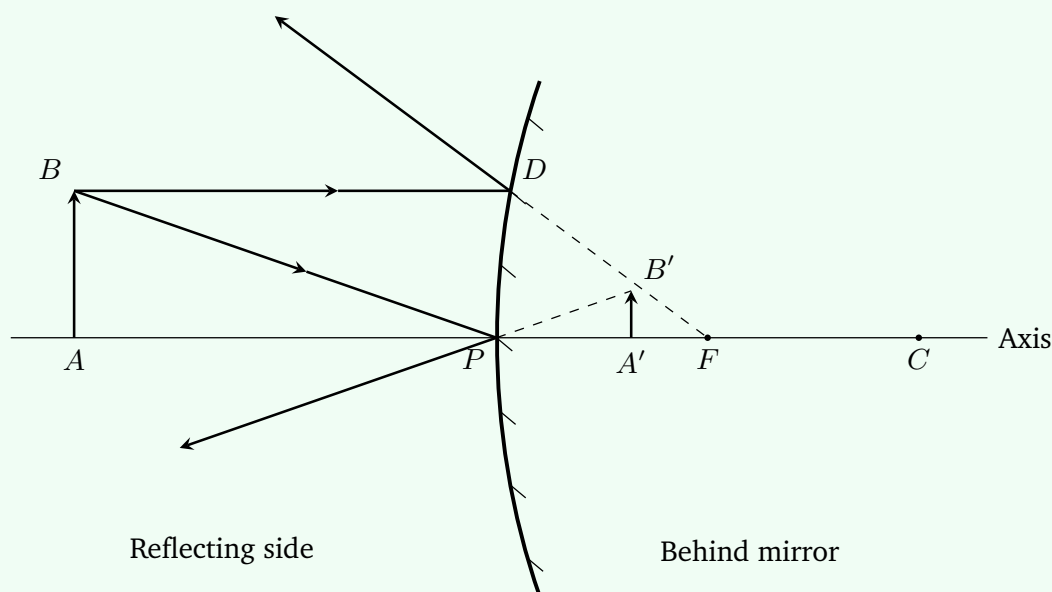
[5 marks]

Solution:

Concept:

- A convex spherical mirror diverges incident rays. Their backward extensions meet behind the mirror, forming a virtual, erect and diminished image of a real object.
- In the Cartesian convention, distances are measured from the pole P , positive along incident light. Thus $u < 0$, $v > 0$ and $f > 0$ for this convex-mirror arrangement. The mirror equation applies to paraxial rays and a small aperture.
- Multi-component lens combinations reduce optical aberrations. For a compound microscope in normal adjustment, the magnitude of angular magnification is $M = |m_o|m_e$, where m_o is objective magnification and $m_e = D/f_e$; $D = 25 \text{ cm}$.

Step 1: (i) Construct the convex-mirror ray diagram Let AB be the object, with A on the principal axis. A ray from B parallel to the axis strikes the mirror at D ; after reflection it diverges as if coming from the principal focus F . Another ray from B strikes the pole P and reflects with equal angles to the principal axis, which is the normal at P . Extend both reflected rays backward. They intersect at B' , and the perpendicular from B' to the axis locates A' . The dotted lines in the diagram are virtual extensions; the solid arrows show actual light propagation. C is the centre of curvature.



Convex mirror: reflected rays diverge and their backward extensions locate the virtual image. The geometry represents the paraxial approximation.

Step 2: (i) Use similar triangles to derive the equation Write the positive lengths $AP = U$, $PA' = V$, $PF = F_0$, and the object and image heights as h and h' . The equal angles at the pole give similar triangles ABP and $A'B'P$, so

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

For a small aperture, the axial displacement of D from the pole is negligible. The incident ray is parallel to the axis, so its height at D is h . Using the similar triangles formed by the backward extension $DB'F$ and the principal axis gives

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

Equating these ratios and rearranging,

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

Now substitute the signed distances $u = -U$, $v = V$, $f = F_0$. This yields the standard Cartesian mirror relation. The use of the small-aperture approximation is essential: marginal rays are affected by spherical aberration.

Step 3: (ii) Explain the use of multi-component lenses A single lens generally does not bring rays of different colours or rays passing through different zones to the same focus. Combining suitably chosen lenses of different glasses and curvatures reduces chromatic aberration and spherical aberration. Thus multi-component objectives and eyepieces produce sharper, clearer images with less colour fringing, which is necessary for observing fine detail in optical instruments.

Step 4: (iii) Find the objective magnification The final image is at infinity, so the microscope is in

normal adjustment. The eyepiece therefore has angular magnification

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

The given total magnification is a magnitude. Dividing it by the eyepiece magnification gives

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

The objective forms a real, inverted intermediate image, so its signed transverse magnification is negative. No $1 + D/f_e$ factor is used here, because that expression applies to an eyepiece adjusted for a final image at the near point.

Step 5: Conclusion (i) The convex mirror forms a virtual, erect, diminished image between P and F , and $\frac{1}{v} + \frac{1}{u} = \frac{1}{f}$. (ii) Multi-component lenses reduce chromatic and spherical aberrations. (iii) The objective magnification has magnitude $\boxed{16}$ (signed value $m_o = -16$).

Quick Tip to Solve: Derive the mirror relation with positive lengths first, then insert Cartesian signs. For a microscope image at infinity, divide total magnification by D/f_e , using the same length units for D and f_e .

OR

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

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

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

Solution:

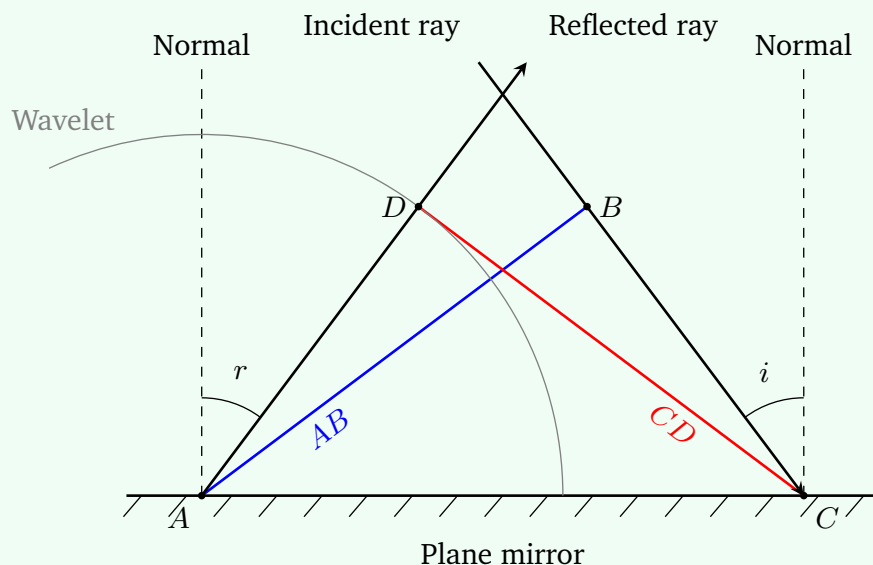
Concept:

- A wavefront is a surface joining points of equal phase. A ray indicates the direction of propagation of light; in an isotropic medium it is normal to the wavefront.
- Huygens' construction obtains a later wavefront as the forward envelope of secondary wavelets emitted from every point of an earlier wavefront. Each wavelet travels at the wave speed of the medium.
- In Young's experiment the fringe width is $\beta = \lambda D/d$, where λ is wavelength, D is slit-to-screen distance and d is slit separation. Bright and dark positions are measured from the central bright fringe.

Step 1: (i) Distinguish a wavefront from a ray A wavefront describes the locus of points oscillating in the same phase at a given instant, whereas a ray describes the direction in which light energy propagates. Thus a wavefront is a surface, while a ray is a directed line. In an isotropic medium, rays are perpendicular to the local wavefront: rays from a point source are radial and its wavefronts are spherical; a parallel beam has plane wavefronts.

Step 2: (ii) State Huygens' principle and construct the reflected wavefront Every point of a wavefront acts as a source of secondary spherical wavelets. These spread with the speed of light in that medium, and their common forward tangent surface at a later instant forms the new wavefront. Let the plane

incident wavefront AB first touch the plane mirror at A . While the disturbance at B travels along the incident ray to C , a secondary reflected wavelet grows from A . After time t , $BC = vt$ and the wavelet radius $AD = vt$. Draw the tangent CD from C to this wavelet. Then CD is the reflected plane wavefront, and AD , normal to it, gives a reflected ray.



Huygens' reflection construction: AB incident wavefront, CD reflected wavefront and $AD = BC = vt$.

Step 3: (ii) Verify both laws of reflection Since incident rays are normal to AB , $\angle ABC = 90^\circ$. A radius is normal to its tangent, so $\angle ADC = 90^\circ$. The right triangles ABC and ADC have the common hypotenuse AC and equal sides $BC = AD = vt$; hence they are congruent. Therefore $\angle BAC = \angle DCA$. The angle between the incident wavefront and mirror equals the angle i between the incident ray and mirror normal. Likewise the angle between the reflected wavefront and mirror equals the reflection angle r . Thus this equality gives $i = r$. The incident ray, mirror normal and reflected ray lie in the plane of this construction. This is the plane of incidence; the wavefront construction therefore also verifies their coplanarity.

Step 4: (iii) Identify the bright and dark fringe positions With the central maximum counted as order zero, the fourth bright fringe is at $y_{B4} = 4\beta$. The first dark fringe is at $\beta/2$, so the second dark fringe is at $y_{D2} = 3\beta/2$. Taking the fringes on the same side of the central maximum, as conventionally intended, their separation is

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

The second dark fringe must not be assigned the bright-fringe position 2β .

Step 5: (iii) Substitute the printed data in SI units Using $d = 3 \times 10^{-3} \text{ m}$, $D = 1.0 \text{ m}$ and $\beta = 2 \times 10^{-3} \text{ m}$,

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

The printed values give an infrared wavelength; they should not be altered to force a visible-light value. The paper does not specify the sides of the two fringes: if they were on opposite sides, their separation would instead be $11\beta/2$, giving $\lambda = 30/11 \mu\text{m}$. The conventional same-side interpretation yields the value above.

Step 6: Conclusion A wavefront is a surface of equal phase and a ray is its propagation normal in an isotropic medium. Huygens' construction gives $i = r$ and coplanarity of the incident ray, reflected ray

and normal. For the usual same-side fringe interpretation, $\lambda = 6.0 \times 10^{-6} \text{ m} = 6.0 \mu\text{m}$.

Quick Tip to Solve: Mark bright orders as $0, 1, 2, \dots$ and dark positions as $1/2, 3/2, 5/2, \dots$ times β before subtracting fringe positions.

33(a). (i) Mention the factors on which the resonant frequency of a series LCR circuit depends. Plot a graph showing variation of impedance of a series LCR circuit with the frequency of the applied a.c. source.

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

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

[5 marks]

Solution:

Concept:

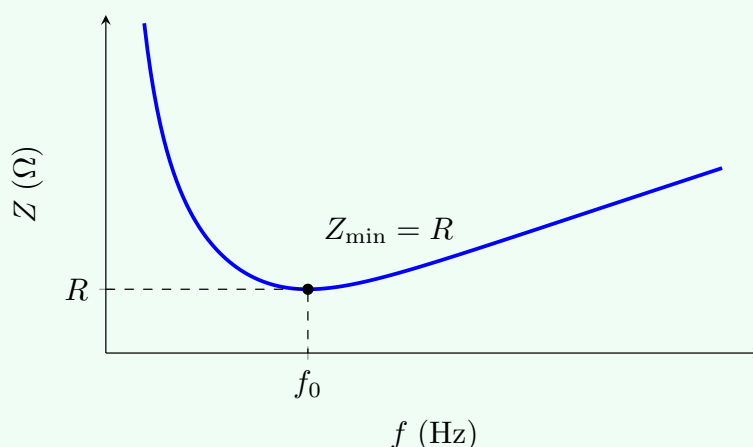
- In a series LCR circuit, the inductive and capacitive reactances are $X_L = 2\pi fL$ and $X_C = 1/(2\pi fC)$, where f is frequency, L inductance and C capacitance. Its impedance is $Z = \sqrt{R^2 + (X_L - X_C)^2}$.
- Resonance occurs when $X_L = X_C$, so the net reactance vanishes and the impedance is its minimum value R .
- A transformer works by mutual induction: a changing magnetic flux Φ in a common core induces emfs $e_p = -N_p d\Phi/dt$ and $e_s = -N_s d\Phi/dt$ in the primary and secondary windings.

Step 1: (i) **Find the factors controlling resonant frequency** Equate the reactances at resonance:

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

Thus the resonant frequency depends on the inductance and capacitance, varying inversely as the square root of each. For the ideal series LCR model it is independent of the resistance and source-voltage amplitude. Increasing either L or C lowers f_0 .

Step 2: (i) **Explain the impedance-frequency graph** At very low frequency, X_C is large and the circuit has a large impedance. As frequency rises towards f_0 , the difference between the reactances decreases. At f_0 , $X_L - X_C = 0$, so $Z_{\min} = R$. Above resonance, X_L increasingly dominates and the impedance rises again. Hence the graph has a minimum at (f_0, R) , rather than zero impedance. The curve diverges as f approaches zero and rises approximately linearly at sufficiently high frequency; it is not symmetric about resonance.



Qualitative impedance-frequency curve for a series LCR circuit; the minimum impedance is R .

Step 3: (ii) Describe the construction and working of a step-up transformer Two insulated windings are wound on a common laminated soft-iron core. The primary winding, with N_p turns, is connected to an a.c. supply. The secondary winding has more turns, $N_s > N_p$, and is connected to the load. The core provides a path for the alternating magnetic flux to link both windings; there is no direct electrical connection between them.

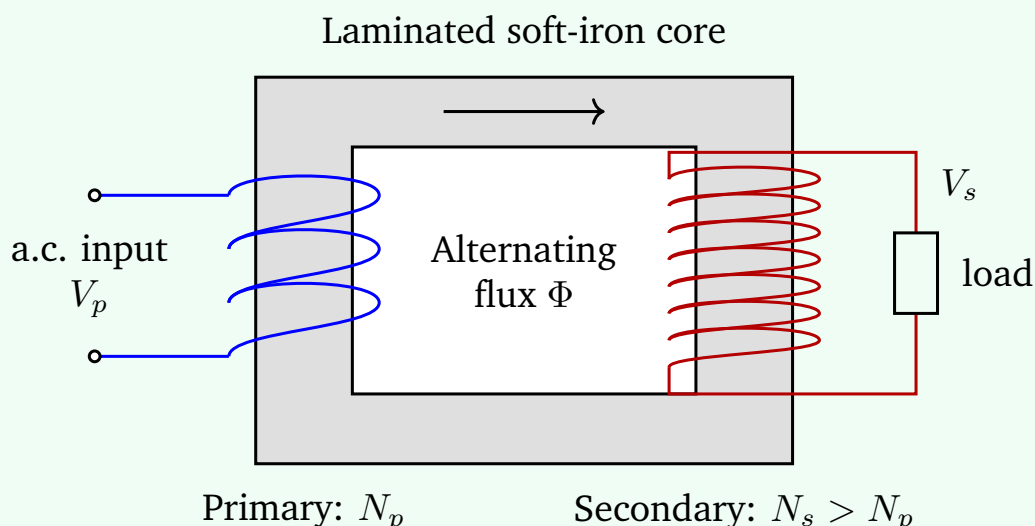
Alternating current in the primary produces a changing flux in the core. By mutual induction, this same changing flux induces an emf in every turn of the secondary. Taking rms magnitudes, and neglecting winding resistance and flux leakage, gives

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

The secondary voltage therefore exceeds the primary voltage. The increased voltage does not create extra energy: for an ideal transformer,

$$V_p I_p = V_s I_s, \quad \frac{I_s}{I_p} = \frac{N_p}{N_s} < 1.$$

A step-up transformer supplies a smaller secondary current at the higher voltage. It requires a changing flux; a steady d.c. supply cannot sustain a secondary induced emf.



Step-up transformer: both windings link the same alternating core flux, with $N_s > N_p$.

Step 4: (iii) Identify two causes of energy loss **Copper loss:** The primary and secondary wires have finite resistance. Currents through them produce heat at the rate $I_p^2 R_p + I_s^2 R_s$.

Eddy-current loss: The alternating flux induces circulating currents in the conducting iron core, which heat the core. Using thin insulated laminations increases the resistance of these circulating paths and reduces this loss. These losses make the output power of a real transformer smaller than its input power.

Step 5: Conclusion The resonant frequency is $f_0 = 1/(2\pi\sqrt{LC})$, and the impedance is minimum, $Z = R$, at resonance. A step-up transformer uses mutual induction with $N_s > N_p$ to obtain $V_s > V_p$. Two energy losses are copper loss in the windings and eddy-current loss in the core.

Quick Tip to Solve: For the resonance graph, first mark the minimum at (f_0, R) . For a step-up transformer, draw more secondary turns and check that voltage rises while the ideal current falls.

OR

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

(ii) An electron is revolving around a proton in an orbit of radius r with a speed v . Obtain expression for magnetic moment associated with the electron. [5 marks]

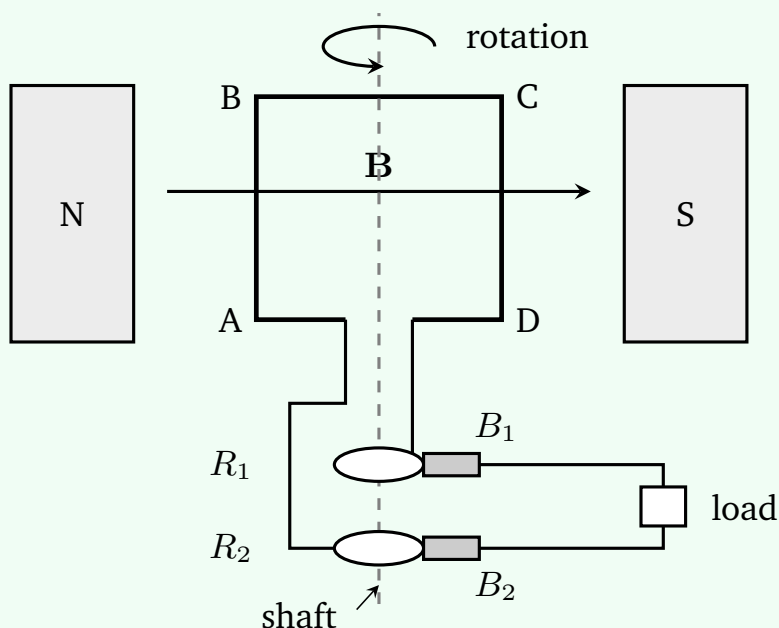
Solution:

Concept:

- Faraday's law gives the induced emf as $\varepsilon = -d(N\Phi)/dt$, where $N\Phi$ is the magnetic flux linkage of an N -turn coil.
- A rotating coil converts mechanical energy into electrical energy. For coil area A , uniform field B and angular speed ω , the flux varies periodically.
- A charge completing one revolution in time T constitutes a current of magnitude $I = |q|/T$. Its magnetic moment is $\mu = IA_{\text{orbit}}$, directed by conventional current.

Step 1: (i) Describe the construction of an ac generator A rectangular insulated copper coil $ABCD$, having N turns and area A , is mounted on a shaft between the north and south poles of a strong

magnet. The shaft rotates about an axis in the plane of the coil and perpendicular to the magnetic field. The two coil ends connect to two separate, complete metallic slip rings R_1 and R_2 , insulated from each other and from the shaft. The coil and rings rotate together. Stationary carbon brushes B_1 and B_2 maintain sliding contact with the rings and connect them to the external load. A turbine or another mechanical source drives the shaft.



Schematic ac generator: the coil and separate slip rings rotate; brushes and the load remain stationary.

Step 2: Explain the working and derive the alternating emf As the coil rotates, the magnetic flux through it changes and an emf is induced by electromagnetic induction. Let the angle between the coil's area normal and the field be $\theta = \omega t$, with the normal parallel to the field at $t = 0$. Then

$$N\Phi = NBA \cos(\omega t), \quad \varepsilon = -\frac{d}{dt} [NBA \cos(\omega t)] = NBA\omega \sin(\omega t).$$

Thus the maximum emf is $\varepsilon_0 = NBA\omega$. The emf is zero when the flux is maximum and is maximum in magnitude when the coil's plane is parallel to the field. After every half revolution, the motion of each side relative to the field reverses, so the induced emf and the current through a resistive load reverse. The slip rings preserve each coil end's connection to its own brush; they do not rectify the output. Mechanical work supplied against the magnetic opposing torque provides the electrical energy delivered to the load.

Step 3: (ii) Calculate the equivalent orbital current Let e be the positive magnitude of the electron's charge. For an orbit of radius r and speed v , the period equals the circumference divided by the speed:

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

Since the electron carries negative charge, conventional current flows around the orbit in the direction opposite to the electron's motion.

Step 4: Obtain the orbital magnetic moment and its direction The circular orbit encloses area πr^2 , so its magnetic moment has magnitude

$$\mu = I\pi r^2 = \frac{ev}{2\pi r} \pi r^2 = \frac{evr}{2}.$$

The moment is perpendicular to the orbital plane, with direction given by the right-hand rule for conventional current. It is therefore opposite to the electron's orbital angular momentum. Since $L = m_e v r$, the corresponding vector relation is $\mu = -e\mathbf{L}/(2m_e)$. The unit of magnetic moment is A m^2 .

Step 5: Conclusion The ac generator uses a rotating coil and slip rings to produce $\varepsilon = NBA\omega \sin(\omega t)$. The revolving electron has magnetic moment of magnitude $\mu = e v r / 2$, directed opposite to its orbital angular momentum.

Quick Tip to Solve: Use complete slip rings for an ac generator. For an orbiting electron, calculate $I = e/T$ first, and reverse the electron's direction to determine conventional current and magnetic moment.