

CBSE Class 12 Physics Question Paper 2024 with Solution PDF-Set 55/4/1



Question Paper with Solutions

Conducted by the Central Board of Secondary Education (CBSE)

Time Allowed: 3 hours

Maximum Marks: 70

General Instructions

- (i) This question paper contains **33** questions. **All questions are compulsory.**
- (ii) Question paper is divided into **FIVE** sections – Section **A, B, C, D** and **E**.
- (iii) **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. Two charges $+q$ each are kept $2a$ distance apart. A third charge $-2q$ is placed midway between them. The potential energy of the system is [1 mark]

- (A) $\frac{q^2}{8\pi\epsilon_0 a}$
(B) $-\frac{6q^2}{8\pi\epsilon_0 a}$
(C) $-\frac{7q^2}{8\pi\epsilon_0 a}$
(D) $\frac{9q^2}{8\pi\epsilon_0 a}$

Correct Answer: (C) $-\frac{7q^2}{8\pi\epsilon_0 a}$

Solution:

Concept:

- The electrostatic potential energy is the sum over distinct pairs: $U = \sum_{i < j} kq_i q_j / r_{ij}$, where $k = 1/(4\pi\epsilon_0)$.
- Like charges contribute positive energy and unlike charges negative energy; each pair must be counted once.

Step 1: Identify the three interacting pairs The two outer charges are separated by $2a$, whereas the middle charge is a distance a from each outer charge. Their pair energies are $kq^2/(2a)$, $-2kq^2/a$, and $-2kq^2/a$, respectively.

Step 2: Add the signed pair energies Keeping the positive outer-pair contribution, we obtain

$$U = \frac{kq^2}{2a} - \frac{2kq^2}{a} - \frac{2kq^2}{a} = -\frac{7kq^2}{2a}.$$

Option A retains only the outer pair. Option B has the wrong coefficient, while option D incorrectly gives a positive total; the two attractive contributions dominate.

Step 3: Conclusion The potential energy is $U = -7q^2/(8\pi\epsilon_0 a)$. Hence, the correct option is (C).

Quick Tip to Solve: List all three pairs first; use distance $2a$ only for the two outer charges and distance a for each middle pair.

2. Two identical small conducting balls B_1 and B_2 are given -7 pC and $+4\text{ pC}$ charges respectively. They are brought in contact with a third identical ball B_3 and then separated. If the final charge on each ball is -2 pC , the initial charge on B_3 was [1 mark]

- (A) -2 pC
- (B) -3 pC
- (C) -5 pC
- (D) -15 pC

Correct Answer: (B) -3 pC

Solution:

Concept:

- Electric charge is conserved when isolated conducting balls are brought into contact: total initial charge equals total final charge.
- Identical balls share the total charge equally in the stated final configuration; three balls with charge q_f each have total charge $3q_f$.

Step 1: Calculate the final total charge Each of the three balls ends with -2 pC , so the final total charge is

$$Q_f = 3(-2) = -6\text{ pC}.$$

The initial combined charge of the first two balls is $-7 + 4 = -3\text{ pC}$.

Step 2: Apply conservation to the third ball If the initial charge on the third ball is Q_3 , conservation gives

$$-3\text{ pC} + Q_3 = -6\text{ pC}, \quad Q_3 = -3\text{ pC}.$$

The other proposed initial charges, -2 , -5 , and -15 pC , give totals -5 , -8 , and -18 pC , respectively, rather than the required -6 pC .

Step 3: Conclusion The initial charge on B_3 was -3 pC . Hence, the correct option is (B).

Quick Tip to Solve: Multiply the final charge per ball by three before subtracting the known initial charges of the first two balls.

3. 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 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 the frequency.
- Einstein's equation is $K_{\max} = h\nu - \phi$, where ϕ is the metal's work function. The threshold frequency is $\nu_0 = \phi/h$.

Step 1: Examine the threshold and kinetic energy statements Below ν_0 , one photon cannot supply the work function, so no photoelectrons are emitted: statement A is correct. For a given metal, ϕ is fixed; Einstein's equation then makes the maximum kinetic energy depend on frequency, not intensity. Statement B is also correct in this usual fixed-metal context. If the metal is changed, its work function must also be specified.

Step 2: Check the remaining statements Photoemission above threshold begins essentially without measurable delay, so C's proposed waiting time is incorrect. Increasing intensity at fixed frequency above threshold increases the photon arrival rate and hence the photoelectric current under otherwise fixed collection conditions; D is incorrect. The printed wording supplies no condition that excludes B while retaining A.

Step 3: Conclusion Options (A) and (B) are both explained by the quantum model for a given metal. As printed, this single-choice question is ambiguous; a unique option cannot be justified.

Quick Tip to Solve: Use $h\nu = \phi + K_{\max}$ to check both threshold and maximum energy; distinguish photon energy from photon arrival rate.

4. 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 the Bohr model of hydrogen, the Coulomb force supplies the centripetal force: $m_e v^2 / r = k e^2 / r^2$, where $k = 1 / (4\pi\epsilon_0)$.
- The allowed angular momenta satisfy $m_e v r = n\hbar$, with $n = 1, 2, 3, \dots$ and $\hbar = h / (2\pi)$.

Step 1: Eliminate the orbital speed Quantisation gives $v = n\hbar / (m_e r)$. Substitution in the force equation gives

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

Thus the radius increases with the square of the orbit number.

Step 2: Identify the dependence on the orbit number Rearranging the equation yields

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

where a_0 is the constant Bohr radius. Linear growth in A misses the square from angular-momentum quantisation. Both inverse dependences in B and D wrongly predict smaller radii for higher orbits.

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

Quick Tip to Solve: Remember the hydrogen pair $r_n \propto n^2$ and $E_n \propto -1/n^2$; the inverse square belongs to energy, not radius.

5. A straight wire is kept horizontally along east-west direction. If a steady current flows in wire from east to west, the magnetic field at a point above the wire will point towards [1 mark]

- (A) East
- (B) West
- (C) North
- (D) South

Correct Answer: (C) North

Solution:

Concept:

- A straight current-carrying wire produces circular magnetic field lines in planes perpendicular to the wire.
- The right-hand thumb rule sets the direction: point the right thumb along current and the curled fingers indicate the magnetic field.

Step 1: Fix the spatial directions Take east as $+\hat{x}$, north as $+\hat{y}$, and vertically upward as $+\hat{z}$. These form a right-handed coordinate system. The current flows toward west, so its direction is $-\hat{x}$; the point is above the wire, in the $+\hat{z}$ direction from it.

Step 2: Apply the right-hand rule above the wire The field direction follows the cross product of the current direction with the direction toward the point:

$$(-\hat{x}) \times \hat{z} = +\hat{y}.$$

East and west lie along the wire and cannot be the circular field's direction here. South would result from reversing the current or choosing a point below the wire, so it does not describe the stated situation.

Step 3: Conclusion The magnetic field at the point above the wire points north. Hence, the correct option is (C).

Quick Tip to Solve: Set east, north and up as a right-handed triad before taking the cross product; reversing current reverses the magnetic field.

6. 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 $\mathbf{M}$ to the applied magnetic field intensity $\mathbf{H}$: $\mathbf{M} = \chi_m \mathbf{H}$.
- A diamagnetic material acquires a weak induced magnetisation opposite to the applied field, so χ_m

is negative with small magnitude.

Step 1: Determine the sign of susceptibility The induced magnetic moments in a diamagnetic material oppose the external field. Consequently, $\mathbf{M}$ and $\mathbf{H}$ point in opposite directions in the susceptibility relation. This requires $\chi_m < 0$, excluding the positive-susceptibility options B and D.

Step 2: Determine the magnitude of the response Ordinary diamagnetic substances are only weakly repelled by a magnetic field; their induced magnetisation is small. Thus $|\chi_m| \ll 1$, rather than the large negative value suggested in C. Equivalently, their relative permeability $\mu_r = 1 + \chi_m$ is slightly less than unity.

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

Quick Tip to Solve: Match weak opposition to the field with small negative susceptibility; weak alignment instead signals paramagnetism.

7. 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: No option gives the ammeter's full-scale current of 1 A; (B) gives the galvanometer current instead.

Solution:

Concept:

- A galvanometer of resistance G is converted to an ammeter by connecting a small shunt resistance S in parallel.
- At full scale, equal branch voltages give $I_g G = (I - I_g)S$, where I is total ammeter current and I_g is the galvanometer current.

Step 1: Distinguish the two full-scale currents The printed ammeter range is 0–1 A. Therefore the current entering the complete ammeter at full-scale deflection is $I = 1\ \text{A}$. Most of this current passes through the shunt; only a small part passes through the galvanometer coil. None of the four printed options equals the total current 1 A.

Step 2: Calculate the coil current implied by the options With $G = 100\ \Omega$ and $S = 0.1\ \Omega$, the coil current 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 if the intended question was about the galvanometer's full-scale current. Options A and C differ from this value by a factor of ten, and D is 100 mA. They describe neither the calculated coil current nor the stated ammeter full-scale current.

Step 3: Conclusion Literally, the ammeter reaches full scale at 1 A, which is absent from the options. Under the intended galvanometer-current interpretation, the answer is approximately 1 mA, option (B).

Quick Tip to Solve: Keep total ammeter current I separate from coil current I_g ; use $I_g = IS/(G + S)$ only for the coil.

8. 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) $R^{\frac{3}{2}}$
- (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 $B = \mu_0 I / (2R)$.
- Magnetic flux through a small coplanar concentric loop is approximately $\Phi = BA$, where $A = \pi r^2$ and the field is normal to its plane.

Step 1: Use the small-loop approximation The printed radius of loop B is $r = R/20$. Since this loop occupies only a small region near the centre of loop A , take the field across it as nearly uniform and equal to the central field.

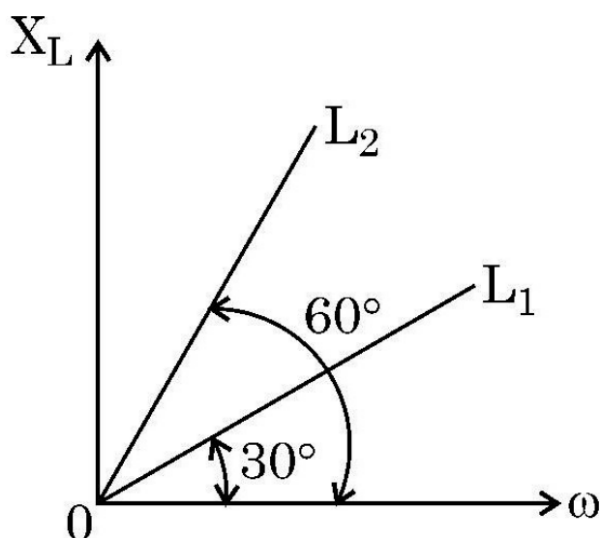
$$\Phi \simeq \frac{\mu_0 I}{2R} \pi \left(\frac{R}{20} \right)^2 = \frac{\mu_0 I \pi R}{800}.$$

Step 2: Compare the radius dependence At fixed current, the field contributes a factor R^{-1} , while the inner-loop area contributes R^2 . Their product therefore scales as R . Option (D) ignores the change in field; neither fractional power in (B) or (C) follows from these factors. Even without the uniform-field approximation, fixed r/R makes the exact flux scale linearly with R .

Step 3: Conclusion The flux linked with loop B is proportional to R . Hence, the correct option is (A).

Quick Tip to Solve: When both loop radii scale together, combine field scaling $1/R$ with area scaling R^2 .

9. Figure shows the variation of inductive reactance X_L of two ideal inductors of inductance L_1 and L_2 with angular frequency ω . The value of $\frac{L_1}{L_2}$ is [1 mark]



- (A) $\sqrt{3}$
- (B) $\frac{1}{\sqrt{3}}$
- (C) 3
- (D) $\frac{1}{3}$

Correct Answer: (D) $\frac{1}{3}$

Solution:

Concept:

- Inductive reactance is $X_L = \omega L$, where ω is angular frequency and L is inductance.
- The slope of an X_L -versus- ω straight line equals its inductance; a line at angle θ to the horizontal has slope proportional to $\tan \theta$.

Step 1: Read both angles from the horizontal In the printed graph the shallower line L_1 is at 30° , and the steeper line L_2 is at 60° , to the ω -axis. The marked 60° is measured from the horizontal, not from the L_1 line.

Step 2: Divide the slopes Both lines use the same axes and scales, so any scale factor cancels in their slope ratio:

$$\frac{L_1}{L_2} = \frac{\tan 30^\circ}{\tan 60^\circ} = \frac{1/\sqrt{3}}{\sqrt{3}} = \frac{1}{3}.$$

Option (C) reverses the ratio. Options (A) and (B) give individual tangent values instead of the ratio of the two slopes.

Step 3: Conclusion The ratio is $L_1/L_2 = 1/3$. Hence, the correct option is (D).

Quick Tip to Solve: For an inductive-reactance graph, take the ratio of tangents of the angles measured from the frequency axis.

10. 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 travelling electromagnetic wave, the electric and magnetic fields oscillate in phase: their maxima, minima and zeros occur together.
- The fields are mutually perpendicular and both are perpendicular to the propagation direction. Spatial perpendicularity does not imply a phase difference.

Step 1: Write fields with a common phase For a plane wave travelling along the positive z -axis, suitable field expressions are

$$\vec{E} = E_0 \cos(kz - \omega t) \hat{x}, \quad \vec{B} = B_0 \cos(kz - \omega t) \hat{y}.$$

Here k is the wave number, ω the angular frequency, and $E_0 = cB_0$ in vacuum. Both fields contain exactly the same oscillatory phase.

Step 2: Separate direction from phase At any fixed position, the two fields rise and fall together, so subtracting their phases gives zero. Option (C) confuses the right angle between the field vectors with phase lag. Option (B) would make the fields opposite in phase, and option (D) would impose a delay that a travelling electromagnetic wave does not have.

Step 3: Conclusion The phase difference between $\vec{E}$ and $\vec{B}$ is zero. Hence, the correct option is (A).

Quick Tip to Solve: Remember: the electric and magnetic fields are perpendicular in direction but synchronous in oscillation.

11. 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 time period. The magnitude of emf induced 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: Maxima occur at $t = (2m + 1)T/4$, $m = 0, 1, 2, \dots$. Option (B) is intended only for odd n ; no option is valid for every printed n .

Solution:

Concept:

- Faraday's law gives the induced emf $\varepsilon = -N d\Phi/dt$, where N is the number of turns and Φ is flux per turn.
- For a fixed coil of area A with its normal parallel to the magnetic field, $\Phi = AB$. The emf magnitude is greatest when the magnitude of the field's time derivative is greatest.

Step 1: Differentiate the magnetic flux Put $B = B_0 \cos(2\pi t/T)$ into Faraday's law:

$$|\varepsilon| = NAB_0 \frac{2\pi}{T} \left| \sin\left(\frac{2\pi t}{T}\right) \right|.$$

Its maximum value is $2\pi NAB_0/T$, attained when the absolute sine equals one.

Step 2: Check the printed integer condition The required times satisfy

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

Thus (B), $t = nT/4$, is the intended choice if n is restricted to odd positive integers. However, the paper explicitly allows $n = 1, 2, 3, 4, \dots$: at $n = 2$, option (B) gives $t = T/2$ and zero emf. Option (A) includes non-maximal times such as $T/8$; (C) and (D) always give zero emf for integer n . Consequently, none of the printed formulas specifies only maxima over its full stated domain.

Step 3: Conclusion The exact condition is $t = (2m + 1)T/4$, for non-negative integers m . The intended option is (B) with odd n , but the printed unrestricted n makes the MCQ defective.

Quick Tip to Solve: Differentiate before choosing a time: sinusoidal flux has maximum induced emf at its zero crossings, every odd quarter-period.

12. 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:

- The Balmer series consists of hydrogen transitions from $n = 3, 4, 5, \dots$ to $n = 2$, with $1/\lambda = R_H(1/4 - 1/n^2)$, where R_H is the Rydberg constant.
- As the upper level n increases, the spectral lines approach a finite series limit. In the usual observed Balmer pattern, successive lines towards this limit become weaker.

Step 1: Track the wavelength spacing Increasing n reduces $1/n^2$, so $1/\lambda$ increases and λ decreases towards $4/R_H$. The change in $1/n^2$ between successive large values of n becomes smaller, so the corresponding wavelengths crowd together near the short-wavelength limit. The lines are neither equally spaced nor increasingly separated.

Step 2: Combine spacing with intensity In the standard hydrogen emission spectrum, the higher Balmer members are progressively fainter towards the series limit. Therefore the required pair of trends is decreasing separation and decreasing intensity. Option (A) contradicts both trends, (B) contradicts the convergence, and (C) gives the right spacing trend but the wrong intensity trend.

Step 3: Conclusion As their wavelengths decrease, Balmer lines appear closer together and weaker in intensity. Hence, the correct option is (D).

Quick Tip to Solve: Towards a spectral-series limit, remember the visual pattern: the lines crowd together and fade.

13. 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 a photon energy $h\nu$ at least equal to the metal's work function ϕ , the minimum energy needed to liberate an electron.
- Photon energy is $E = hc/\lambda$; shorter wavelengths carry more energy. Zinc requires ultraviolet radiation for ordinary photoelectric emission.

Step 1: Evaluate the assertion Yellow light lies in the visible region and does not have sufficient photon energy to eject electrons from zinc. Thus irradiation by yellow light does not produce the claimed photoelectric emission, and Assertion (A) is false.

Step 2: Evaluate the reason A representative yellow wavelength of about 590 nm gives photon energy $1240/590 \simeq 2.1$ eV, below zinc's work function of roughly 4.3 eV. These approximate values illustrate that yellow-photon energy is less than, not more than, the work function. Reason (R) is therefore false.

Step 3: Check the explanatory link and code Both statements fail the threshold-energy condition, so the reason cannot explain the asserted emission. Options (A) and (B) require both statements to be true, while (C) requires the assertion to be true. The printed code (D) is the one for both statements being false.

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; increasing intensity cannot overcome a photon energy below threshold.

14. 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 of resistance describes how resistance changes with temperature: positive means resistance rises, and negative means it falls.
- Conductivity depends on carrier density and mobility. For a semiconductor, $\sigma = e(n\mu_e + p\mu_h)$, where n, p are electron and hole densities and μ_e, μ_h are their mobilities.

Step 1: Evaluate the assertion In metals, rising temperature increases lattice vibrations and electron scattering, so resistance increases. In the standard semiconductor regime, heating increases the charge-carrier population sufficiently that resistance decreases. Thus metals have a positive temperature coefficient and *p*-type semiconductors have a negative one, as stated. The assertion is true.

Step 2: Evaluate the reason Metallic conduction is due to negatively charged free electrons. In a *p*-type semiconductor, holes are the majority carriers and behave as positively charged carriers. The reason correctly identifies the carriers and is true.

Step 3: Test whether the reason explains the assertion The sign of the carrier charge does not determine whether resistance increases or decreases on heating. The relevant changes are in scat-

tering, mobility and carrier concentration. An n -type semiconductor also ordinarily has a negative temperature coefficient despite having electrons as majority carriers. Therefore the reason does not explain the assertion. Option (A) incorrectly claims an explanatory link; (C) and (D) incorrectly reject true statements.

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

Quick Tip to Solve: For temperature coefficients, ask how carrier density and scattering change; the positive or negative charge of a carrier is irrelevant.

15. 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 random thermal velocities in all directions even in the absence of an applied electric field.
- Drift velocity, $\vec{v}_d$, is the small average velocity acquired under an applied field; it is opposite to the field for electrons.

Step 1: Evaluate the assertion Each electron continues its random motion and undergoes collisions while the electric field produces a small directed bias in the motion. Thus a nonzero average velocity does not imply that every instantaneous electron velocity points in one direction. Assertion (A) is true.

Step 2: Evaluate the reason The systematic drift is superposed on the much larger random velocities. Symbolically, $\vec{v} = \vec{v}_{\text{random}} + \vec{v}_d$, where the random contribution averages to zero over many electrons. Reason (R) is true.

Step 3: Test the explanatory link Since the random component is large and points in different directions, the small common drift cannot make all instantaneous velocities parallel. This directly explains the assertion. Option (B) misses this causal link, while (C) and (D) incorrectly reject true statements.

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

Quick Tip to Solve: Distinguish an individual electron's instantaneous velocity from the average drift velocity of the electron population.

16. 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 produces constructive and destructive interference, redistributing intensity across the pattern.
- Energy is conserved: a dark fringe has reduced intensity, balanced by increased intensity elsewhere in the complete interference or diffraction pattern.

Step 1: Evaluate the assertion Where waves reinforce, their resultant amplitude and intensity increase, producing a bright fringe. Where waves cancel, intensity decreases, producing a dark fringe. Diffraction similarly distributes light into maxima and minima. Assertion (A) is true.

Step 2: Evaluate the reason Interference and diffraction do not destroy energy. They change where the energy reaches the observation screen. When the complete pattern is considered, the energy removed from darker regions appears in brighter regions. The statement that energy is not conserved is therefore false.

Step 3: Test the explanatory link A false reason cannot explain the true assertion. Options (A) and (B) incorrectly treat the reason as true; option (D) incorrectly treats the assertion as false. The observed pattern follows superposition while obeying conservation of energy.

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

Quick Tip to Solve: A dark fringe means energy is absent at that location, not that light energy has been destroyed in the whole pattern.

Section B (10 marks)

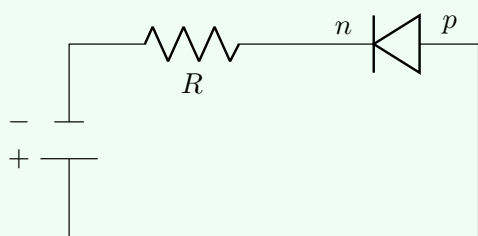
17. Draw the circuit diagram of a p - n junction diode in (i) forward biasing and (ii) reverse biasing. Also draw its I - V characteristics in the two cases. [2 marks]

Solution:

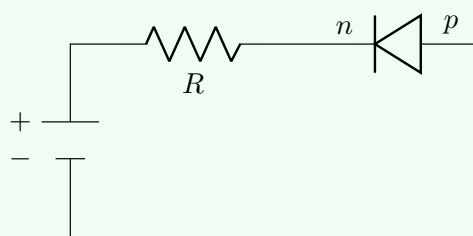
Concept:

- A diode is forward biased when its p -side is connected to the positive terminal and its n -side to the negative terminal; reversing the connections gives reverse bias.
- Take diode voltage $V = V_p - V_n$ and conventional current I positive from p to n . Forward bias reduces the junction barrier, while reverse bias increases it.

Step 1: Connect the diode in each bias In circuit (i), the positive cell terminal connects to p , and the negative terminal connects through the limiting resistor R to n . In circuit (ii), the cell is reversed: p is connected to negative and n to positive. The bar of the diode symbol identifies the n -side. The resistor limits the current through the diode.



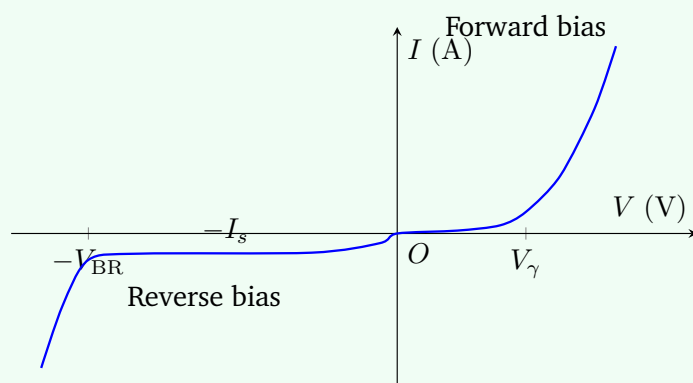
(i) Forward bias



(ii) Reverse bias

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

Step 2: Sketch the current-voltage characteristics In forward bias, the current is initially small and then rises rapidly beyond the knee voltage V_γ . In reverse bias, a small minority-carrier saturation current flows in the negative direction and remains nearly constant until breakdown at $V = -V_{BR}$. Beyond breakdown its magnitude rises sharply. The reverse-current scale is exaggerated in the sketch to make this much smaller current visible.



Schematic diode characteristic; reverse current is shown on an enlarged scale.

Step 3: Conclusion Forward bias has p positive and n negative, with a rapidly increasing forward

current after the knee. Reverse bias has p negative and n positive, with only a small reverse saturation current before breakdown.

Quick Tip to Solve: Identify the cathode bar as the n -side, then check the cell polarity; plot reverse voltage and reverse current on the negative axes.

18. A proton and α -particle are accelerated through different potentials V_1 and V_2 respectively so that they have the same de Broglie wavelengths. Find $\frac{V_1}{V_2}$. [2 marks]

Solution:

Concept:

- The de Broglie wavelength is $\lambda = h/p$, where h is Planck's constant and p is momentum. Equal wavelengths therefore require equal momenta.
- For a particle of mass m and charge q , accelerated from rest through a potential difference V , $qV = p^2/(2m)$, so $p = \sqrt{2mqV}$ in the non-relativistic treatment.

Step 1: Express the momentum of each particle Let the proton mass be m_p and its charge be e . An alpha particle has mass approximately $4m_p$ and charge $2e$. The kinetic energies acquired are eV_1 and $2eV_2$, respectively. Hence,

$$p_p^2 = 2m_p eV_1, \quad p_\alpha^2 = 2(4m_p)(2e)V_2.$$

Step 2: Apply equality of wavelengths Since $h/p_p = h/p_\alpha$, the momenta, and therefore their squares, are equal. Substituting their expressions gives

$$2m_p eV_1 = 16m_p eV_2 \Rightarrow V_1 = 8V_2.$$

Both the fourfold mass and the twofold charge of the alpha particle enter this comparison; using only either factor would give an incorrect ratio.

Step 3: Conclusion The required potential ratio is $V_1/V_2 = 8$, or $V_1 : V_2 = 8 : 1$.

Quick Tip to Solve: Equal de Broglie wavelengths mean equal momentum: immediately set the products mqV equal for the two particles.

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:

- Within a prism, the angles made by the internal ray with the normals to its two refracting faces obey $r_1 + r_2 = A$, where A is the prism angle.
- Snell's law at a glass-medium boundary is $\mu \sin i = n_m \sin e$, where μ and n_m are the absolute refractive indices of glass and the surrounding medium.

Step 1: Find the internal incidence at the second face The incident ray is normal to the first face, so it enters without deviation and $r_1 = 0^\circ$. The angle of an equilateral prism is $A = 60^\circ$. Using the

prism-angle relation,

$$r_2 = A - r_1 = 60^\circ - 0^\circ = 60^\circ.$$

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

Step 2: Apply the grazing-emergence condition An emergent ray grazing the second face makes $e = 90^\circ$ with its normal. Thus the internal incidence is exactly the critical angle for the glass-medium boundary. Snell's law gives

$$\mu \sin 60^\circ = n_m \sin 90^\circ \Rightarrow n_m = \frac{\sqrt{3}}{2} \mu.$$

The ratio $n_m/\mu = \sqrt{3}/2 < 1$ confirms that the ray travels from the optically denser glass into a rarer medium at this boundary.

Step 3: Conclusion The refractive index of the surrounding medium is $n_m = \frac{\sqrt{3}}{2} \mu$.

Quick Tip to Solve: Normal entry makes the first refraction angle zero; grazing exit makes the emergence angle 90° , so use Snell's law at the second face.

20. Two electric heaters have power ratings P_1 and P_2 , at voltage V . They are connected in series to a dc source of voltage V . Find the power consumed by the combination. Will they consume the same power if connected in parallel across the same source? [2 marks]

Solution:

Concept:

- A resistive heater of resistance R consumes power $P = V^2/R$ when the voltage across it is V . Its rated power specifies its resistance at the rated operating condition.
- Series resistances add, while parallel heaters each receive the full source voltage. Take the heater resistances as constant, as in the ideal resistive-heater model.

Step 1: Express each heater's resistance Both powers are specified at the same voltage V , so the individual resistances are

$$R_1 = \frac{V^2}{P_1}, \quad R_2 = \frac{V^2}{P_2}.$$

A heater with the larger rated power therefore has the smaller resistance; the ratings cannot simply be added when the heaters are placed in series.

Step 2: Calculate the series power The same current flows through both heaters and the source voltage is shared between them. Hence

$$R_s = R_1 + R_2 = \frac{V^2(P_1 + P_2)}{P_1 P_2},$$
$$P_s = \frac{V^2}{R_s} = \frac{P_1 P_2}{P_1 + P_2}.$$

Step 3: Compare with the parallel connection In parallel each heater is again connected directly

across its rated voltage V . Its power is therefore its own rated value, giving

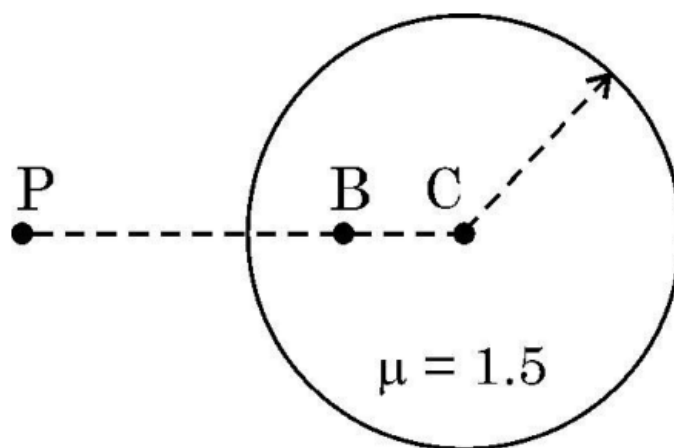
$$P_p = \frac{V^2}{R_1} + \frac{V^2}{R_2} = P_1 + P_2.$$

For positive ratings, the series power is smaller than either rating, whereas the parallel power is larger than either rating.

Step 4: Conclusion The combination consumes $P_s = P_1 P_2 / (P_1 + P_2)$ in series. It does **not** consume the same power in parallel: $P_p = P_1 + P_2$, which is greater.

Quick Tip to Solve: Convert each rating to resistance using $R = V^2/P$ before combining heaters; add rated powers only when each receives its rated voltage.

21(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 figure. Find the nature and position of the image of the bubble as seen by an observer at point P . [2 marks]



Solution:

Concept:

- Refraction at a spherical interface obeys $\frac{n_2}{v} - \frac{n_1}{u} = \frac{n_2 - n_1}{R}$, where u , v , and R are measured from the surface pole.
- In the Cartesian convention, distances along incident light are positive. A negative image distance represents a virtual image on the incident side of a refracting surface.

Step 1: Identify the near surface and assign signs The observer P is to the left of the sphere. Light travels from bubble B through glass to the left-hand surface and then into air. Let this surface pole be S , taking leftwards as positive. The bubble is between S and centre C , so

$$SB = SC - CB = 40 - 20 = 20 \text{ cm.}$$

Both B and C lie to the right of S ; therefore $u = -20$ cm, $R = -40$ cm, $n_1 = 1.5$, and $n_2 = 1$.

Step 2: Apply the spherical refraction formula Substituting with all distances in centimetres,

$$\begin{aligned}\frac{1}{v} - \frac{1.5}{-20} &= \frac{1 - 1.5}{-40}, \\ \frac{1}{v} + \frac{3}{40} &= \frac{1}{80}, \\ \frac{1}{v} &= -\frac{5}{80}, \quad v = -16 \text{ cm}.\end{aligned}$$

The negative sign places the image inside the glass, on the bubble's side of the surface. Emerging rays diverge and their backward extensions meet there.

Step 3: Conclusion The bubble forms a **virtual image**, 16 cm inside the surface nearest P . Equivalently, the image lies 24 cm from C towards P , between the actual bubble and the near surface.

Quick Tip to Solve: First measure the bubble's distance from the surface facing the observer: here it is $40 - 20$, not 20 from the centre in the refraction formula.

OR

21(b). In normal adjustment, for a refracting telescope, the distance between objective and eye piece 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 final image of an astronomical refracting telescope is at infinity. Its lens separation is $L = f_o + f_e$, where f_o and f_e are the objective and eyepiece focal lengths.
- The magnitude of angular magnifying power is $|M| = f_o/f_e$. The usual negative sign of signed magnification indicates an inverted image; the given power 19 is its magnitude.

Step 1: Form the two focal-length equations The objective forms the intermediate image at its focal plane. For normal adjustment this plane coincides with the first focal plane of the eyepiece, allowing parallel rays to emerge. The given separation therefore implies

$$f_o + f_e = 1.00 \text{ m}.$$

The specified angular magnification gives

$$\frac{f_o}{f_e} = 19, \quad f_o = 19f_e.$$

Step 2: Solve for the eyepiece and objective Substitute the focal-length ratio into the separation equation:

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

These values give a sum of 1.00 m and a ratio of 19, satisfying both conditions. Both lenses are

converging, so both focal lengths are positive.

Step 3: Conclusion The objective focal length is $f_o = 95 \text{ cm}$, and the eyepiece focal length is $f_e = 5.0 \text{ cm}$.

Quick Tip to Solve: For normal adjustment use $f_e = L/(|M| + 1)$, then $f_o = L - f_e$; the objective must have the larger focal length.

Section C (21 marks)

22. (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 reactions release energy when the products have greater total binding energy than the reactants. The corresponding loss of mass appears as energy, $E = \Delta mc^2$.
- The number of nuclei in mass m is $N = (m/M)N_A$, where M is the molar mass and $N_A = 6.022 \times 10^{23} \text{ mol}^{-1}$. Total fission energy equals the number of fissions multiplied by energy per fission.

Step 1: (a) Distinguish the two nuclear processes **Fission:** A heavy nucleus, such as uranium-235 or plutonium-239, splits into two lighter nuclei, usually after absorbing a neutron. Energy and additional neutrons are released; these neutrons can produce a chain reaction in suitable conditions.

Fusion: Two light nuclei combine to form a heavier nucleus, releasing energy. Very high temperature is required in ordinary thermonuclear fusion to help nuclei overcome their electrostatic repulsion. Thus, fission breaks a heavy nucleus apart, whereas fusion joins light nuclei together. Both can release energy because their products are more tightly bound per nucleon.

Step 2: (b) Count the plutonium nuclei in one gram Pure plutonium-239 has molar mass approximately 239 g mol^{-1} . Therefore the number of nuclei in the given sample is

$$N = \frac{1 \text{ g}}{239 \text{ g mol}^{-1}} (6.022 \times 10^{23} \text{ mol}^{-1}) \\ \simeq 2.520 \times 10^{21}.$$

Each atom contains one plutonium nucleus. Since every nucleus is stated to undergo fission, this is also the total number of fission events.

Step 3: Multiply by the average energy per event Each fission releases 180 MeV on average, so

$$E = N \times 180 \text{ MeV} \\ = (2.520 \times 10^{21})(180) \text{ MeV} \\ \simeq 4.535 \times 10^{23} \text{ MeV}.$$

The requested unit is already MeV, so no conversion to joules is needed. The atomic number 94 is not the molar mass and must not replace 239 in the atom count.

Step 4: Conclusion Fission splits heavy nuclei; fusion combines light nuclei. Complete fission of 1 g of plutonium-239 releases approximately 4.54×10^{23} MeV.

Quick Tip to Solve: For total fission energy use $E = (m/M)N_A E_f$; keep mass and molar-mass units consistent, and retain MeV when that is the requested unit.

23. The electric field in a region is given by $\vec{E} = (10x + 4)\hat{i}$, where x is in m and E is in N/C. Calculate the amount of work done in taking a unit charge from

(i) (5 m, 0) to (10 m, 0)

(ii) (5 m, 0) to (5 m, 10 m)

[3 marks]

Solution:

Concept:

- Work done by an electric field on a charge q is $W_{\text{field}} = q \int_A^B \vec{E} \cdot d\vec{r}$. Only displacement parallel to the field contributes.
- For slow transport without change in kinetic energy, external work is $W_{\text{ext}} = \Delta U = q(V_B - V_A) = -W_{\text{field}}$. Here a unit positive charge means $q = 1$ C.

Step 1: Set up the work integral Since $\vec{E} = (10x + 4)\hat{i}$, the field is along the positive x -axis and its magnitude varies with position. We therefore integrate rather than multiply one endpoint's field by the total distance. With $d\vec{r} = dx\hat{i} + dy\hat{j}$, the scalar product is

$$\vec{E} \cdot d\vec{r} = (10x + 4) dx.$$

Consequently the potential difference depends only on the initial and final x -coordinates.

Step 2: Evaluate part (i), along the field The limits are $x = 5$ m and $x = 10$ m, while y remains zero:

$$\begin{aligned} W_{\text{field}} &= 1 \int_5^{10} (10x + 4) dx \\ &= [5x^2 + 4x]_5^{10} \\ &= (500 + 40) - (125 + 20) = 395 \text{ J.} \end{aligned}$$

The field does positive work because the positive charge moves along it. The potential falls by 395 V, so the external agent does -395 J during slow transport.

Step 3: Evaluate part (ii), perpendicular to the field Along the vertical path $x = 5$ m, $dx = 0$. Although the field is nonzero, it is perpendicular to every displacement element:

$$W_{\text{field}} = 1 \int_0^{10} (54\hat{i}) \cdot (dy\hat{j}) = 0.$$

Both endpoints lie on the same equipotential, and the external work is also zero.

Step 4: Conclusion The work done by the electric field is (i) 395 J, (ii) 0 J. If work done in taking the charge denotes the external work for slow transport, the corresponding signed values are (i) -395 J, (ii) 0 J.

Quick Tip to Solve: First use the dot product: only the change in x matters here. State whether your sign refers to the field or to the external agent.

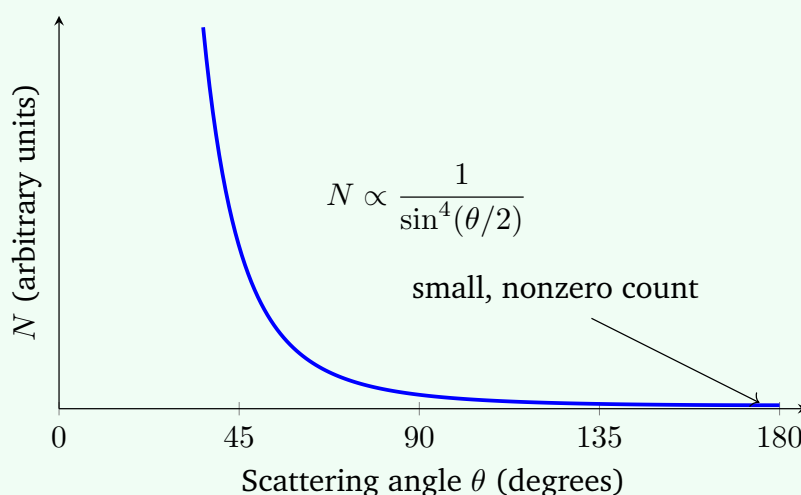
24. Draw the graph showing variation of scattered particles detected (N) with the scattering angle (θ) in Geiger-Marsden experiment. Write two conclusions that you can draw from this graph. Obtain the expression for the distance of closest approach in this experiment. [3 marks]

Solution:

Concept:

- Rutherford scattering gives $N(\theta) \propto 1/\sin^4(\theta/2)$ for a fixed detector solid angle, where N is the number of detected alpha particles and θ is the scattering angle.
- In a head-on encounter, the incident alpha particle's kinetic energy is converted into electrostatic potential energy at the turning point. The alpha particle has charge $+2e$, and the target nucleus has charge $+Ze$.

Step 1: Plot the observed angular dependence The count is very large at small scattering angles, falls rapidly as θ increases, and is very small but nonzero near 180° . The sketch shows this trend in arbitrary count units. The ideal scattering formula is singular at zero angle, so the curve starts at a small positive angle; the undeflected beam is not a finite point on this theoretical curve.



Schematic alpha-particle count versus scattering angle; the large-angle count remains small and nonzero.

Step 2: State two conclusions from the scattering pattern (1) Most alpha particles pass through the foil with little or no deflection. Thus most of the atomic volume is empty space.

(2) A very small fraction undergo large deflections or even return backwards. Hence the atom's positive charge and almost all its mass are concentrated in a very small, dense central nucleus. Its repulsion can turn an alpha particle through a large angle only in a rare close encounter.

Step 3: Use energy conservation for closest approach Let the incident alpha particle have kinetic energy $K = \frac{1}{2}mv^2$ far from a heavy nucleus, where the interaction energy is taken as zero. For a head-on approach the particle is momentarily at rest at separation $r_{\min}$. Neglecting nuclear recoil,

$$K = \frac{1}{4\pi\epsilon_0} \frac{(2e)(Ze)}{r_{\min}}.$$

Rearranging gives

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

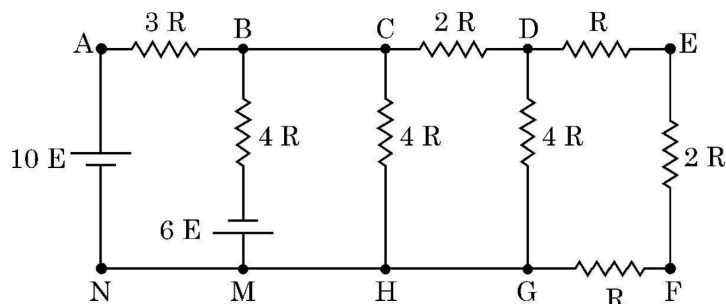
This is the centre-to-centre separation for the head-on turning point; it decreases when the incident kinetic energy increases.

Step 4: Conclusion The count falls steeply with angle, showing a mostly empty atom with a tiny massive positive nucleus. The head-on distance of closest approach is $r_{\min} = \frac{2Ze^2}{4\pi\epsilon_0 K}$.

Quick Tip to Solve: For closest approach, set the initial kinetic energy equal to Coulomb potential energy and remember the alpha particle carries $2e$, not e .

25. Find the current in branch BM in the network shown:

[3 marks]



Solution:

Concept:

- Resistors in series add; parallel resistors obey $1/R_{\text{eq}} = 1/R_1 + 1/R_2$. Points joined by ideal wires have equal potential.
- Kirchhoff's junction rule states that the algebraic sum of currents leaving a node is zero. In a resistor, current from potential V_1 to V_2 is $(V_1 - V_2)/R$.

Step 1: Read the cell polarities and identify common nodes Take the common wire N, M, H, G as zero potential. The long plate of the $10E$ cell is connected to A , so $V_A = 10E$. In branch BM , the long plate of the $6E$ cell is connected to M ; therefore its upper terminal, denoted X , has potential $V_X = -6E$. The points B and C are joined by a wire and have common potential V .

Step 2: Reduce the passive network to the right of B The path $D \rightarrow E \rightarrow F \rightarrow G$ contains three series resistors:

$$R + 2R + R = 4R.$$

This path is parallel to the direct DG resistor $4R$, giving $2R$ between D and G . Adding the CD resistor $2R$ gives $4R$ along the reduced path from C through D to G . This is parallel to $CH = 4R$, so the entire passive network between $B = C$ and the bottom wire is

$$R_{\text{right}} = 4R \parallel 4R = 2R.$$

Branch BM , which contains a cell, is kept separate from this reduction.

Step 3: Apply the junction rule at B Express all three branch currents as leaving B :

$$\frac{V - 10E}{3R} + \frac{V + 6E}{4R} + \frac{V}{2R} = 0.$$

Multiplication by $12R$ gives

$$4V - 40E + 3V + 18E + 6V = 0,$$

$$13V = 22E, \quad V = \frac{22E}{13}.$$

The current through the $4R$ resistor in BM , measured downwards, is

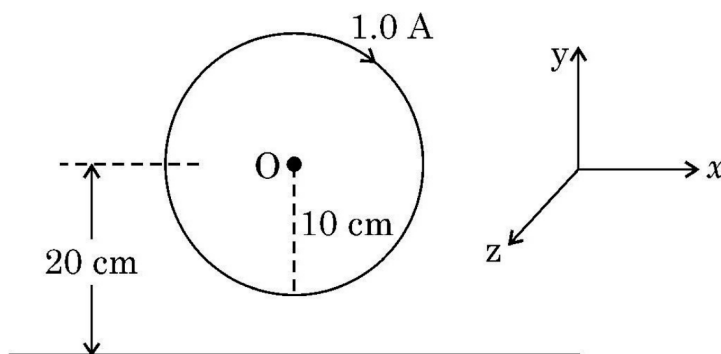
$$I_{BM} = \frac{V - V_X}{4R} = \frac{22E/13 + 6E}{4R} = \frac{25E}{13R}.$$

Its positive sign confirms the assumed downward direction through the resistor and cell.

Step 4: Conclusion The current in branch BM is $I_{BM} = \frac{25E}{13R}$, flowing from B to M . It is in amperes when E is in volts and R is in ohms.

Quick Tip to Solve: Reduce the right-hand ladder first, then read the unequal cell polarities carefully: the upper terminal of the $6E$ cell is at $-6E$.

26. A circular loop of radius 10 cm carrying current of 1.0 A lies in x - y plane. A long straight wire lies in the same plane parallel to x -axis at a distance of 20 cm as shown in figure. Find the direction and value of current that has to be maintained in the wire so that the net magnetic field at O is zero. [3 marks]



Solution:

Concept:

- A single circular loop of radius R carrying current I_0 produces a field $B_{\text{loop}} = \mu_0 I_0 / (2R)$ at its centre, normal to its plane.
- An infinitely long straight wire carrying current I produces $B_{\text{wire}} = \mu_0 I / (2\pi d)$ at perpendicular distance d . Use the right-hand rule to determine its direction.
- For zero resultant magnetic field, the two vector fields must have equal magnitudes and opposite directions.

Step 1: Read the distances and the loop-field direction The loop radius is $R = 10 \text{ cm} = 0.10 \text{ m}$, its current is $I_0 = 1.0 \text{ A}$, and the centre-to-wire distance is $d = 20 \text{ cm} = 0.20 \text{ m}$. The marked distance is measured from the level of O , not from the lower edge of the loop. The arrow on the loop is clockwise in the printed view, so the right-hand rule gives the loop's field into the plane, along $-z$.

$$B_{\text{loop}} = \frac{4\pi \times 10^{-7} \times 1.0}{2 \times 0.10} = 2\pi \times 10^{-6} \text{ T}.$$

Step 2: Choose the wire-current direction and equate magnitudes The wire must produce a field out of the plane, along $+z$, at O . Since O lies above the wire, a current from left to right, parallel to the

positive x -axis, has the required direction: $\hat{x} \times \hat{y} = \hat{z}$. Equating the magnitudes then gives

$$\frac{\mu_0 I}{2\pi d} = \frac{\mu_0 I_0}{2R},$$

$$I = \frac{\pi d I_0}{R} = \frac{\pi(0.20)(1.0)}{0.10} = 2\pi \text{ A}.$$

Reversing this current would make the two magnetic fields point in the same direction, so their magnitudes would add instead of cancelling.

Step 3: Conclusion Maintain a current $I = 2\pi \text{ A} \approx 6.28 \text{ A}$ in the straight wire from left to right, along the positive x -axis. Its field at O cancels the clockwise loop's field.

Quick Tip to Solve: Use the centre-to-wire distance, then cancel $\mu_0/2$ to get $I/I_0 = \pi d/R$; settle the current direction separately with the right-hand rule.

27. Name the electromagnetic waves with their wavelength range which are used for

(i) FM radio broadcast

(ii) detection of fracture in bones

(iii) treatment of muscular strain

[3 marks]

Solution:

Concept:

- Electromagnetic waves are classified by wavelength λ or frequency ν , related in vacuum by $c = \nu\lambda$, where $c = 3.0 \times 10^8 \text{ m s}^{-1}$.
- Their interaction with matter determines their uses: radio waves carry broadcasts, penetrating X-rays form bone images, and absorbed infrared radiation produces heating. Spectral boundaries are approximate.

Step 1: Identify the waves used for FM broadcasting (i) FM broadcasts use **radio waves**, specifically the very-high-frequency band. The usual FM broadcast frequencies are 88–108 MHz. The corresponding wavelength interval follows from $\lambda = c/\nu$:

$$\lambda_{\min} = \frac{3.0 \times 10^8}{108 \times 10^6} = 2.78 \text{ m}, \quad \lambda_{\max} = \frac{3.0 \times 10^8}{88 \times 10^6} = 3.41 \text{ m}.$$

Thus the relevant waves have wavelengths of about 2.8–3.4 m. The broad radio-wave region is conventionally represented as wavelengths longer than about 0.1 m; FM uses only a small part of it.

Step 2: Identify the waves used to detect bone fractures (ii) **X-rays** are used, with the approximate spectral wavelength range 10^{-12} – 10^{-9} m , or 10^{-3} –1 nm. Bone absorbs X-rays more strongly than surrounding soft tissue. This difference produces contrast on the detector, allowing a fracture to be seen; visible light cannot penetrate the body to provide the same image.

Step 3: Identify the waves used for muscular strain (iii) **Infrared waves** are used, with wavelengths approximately 7×10^{-7} – 10^{-3} m , or 700 nm to 1 mm. Absorption of infrared radiation warms tissue,

which accounts for its use in heat treatment of muscular strain. This use depends on its thermal effect, rather than the penetrating imaging action of X-rays.

Step 4: Conclusion (i) Radio waves: FM wavelengths approximately 2.8–3.4 m. (ii) X-rays: approximately 10^{-12} – 10^{-9} m. (iii) Infrared waves: approximately 7×10^{-7} – 10^{-3} m.

Quick Tip to Solve: Associate broadcast with radio, bone imaging with X-rays, and heat therapy with infrared; for FM, invert the frequency endpoints when using $\lambda = c/\nu$.

28(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 relates the magnetic flux linkage of one coil to the current in another coil: $N_2\Phi_{21} = MI_1$. Here Φ_{21} is the flux through each turn of coil 2 due to current I_1 in coil 1.
- A changing current induces an emf $\varepsilon_2 = -M dI_1/dt$. For a long air-core solenoid of length l and N turns, the interior field is $B = \mu_0 NI/l$, while the exterior field is negligible.

Step 1: Define mutual inductance and state its SI unit (i) The mutual inductance of two coils is the magnetic flux linkage with either coil per unit current in the other coil. Equivalently, it is the magnitude of induced emf in one coil when the current in the other changes at unit rate. Its SI unit is the **henry**, denoted H:

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

Two coils have mutual inductance 1 H if a current change of 1 A s^{-1} in one induces an emf of magnitude 1 V in the other.

Step 2: Find the common magnetic flux (ii) Let solenoid 1 be the inner solenoid of radius r_1 and N_1 turns. Pass current I_1 through it. For long, coaxial, air-core solenoids of common length l , neglecting end effects,

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

This field occupies essentially the inner cross-sectional area $A_1 = \pi r_1^2$. Although the outer solenoid has larger radius r_2 , the field due to the inner one is negligible in the annular area outside r_1 . Consequently the flux through each outer turn is

$$\Phi_{21} = B_1 A_1 = \frac{\mu_0 N_1 I_1 \pi r_1^2}{l}.$$

Step 3: Use the outer solenoid's total flux linkage All N_2 turns of the outer solenoid link this flux. Therefore,

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

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

Interchanging the coils gives the same result: the outer solenoid's field links each inner turn over area πr_1^2 . Thus $M_{12} = M_{21}$, as expected for mutual inductance.

Step 4: Conclusion Mutual inductance is flux linkage in one coil per unit current in the other and is measured in henries. For the two long air-core coaxial solenoids,

$$M = \frac{\mu_0 N_1 N_2 \pi r_1^2}{l}.$$

The smaller radius sets the common flux area because $r_2 > r_1$.

Quick Tip to Solve: For coaxial solenoids, use the smaller cross-sectional area in $M = \mu_0 N_1 N_2 A/l$, and multiply the flux per turn by the receiving coil's number of turns.

OR

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

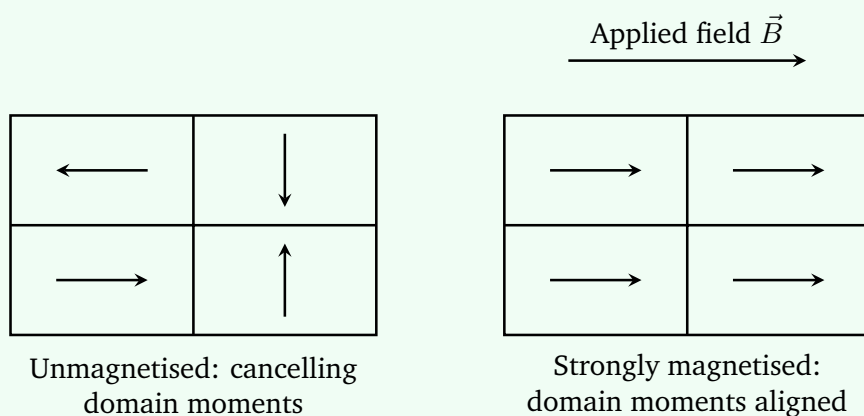
Solution:

Concept:

- Ferromagnetic materials are strongly attracted by a magnet and acquire a large magnetisation in the direction of an applied magnetic field; iron, cobalt and nickel are examples.
- A magnetic domain is a small region containing many atomic magnetic moments aligned parallel by their mutual interaction. Each domain has a large spontaneous magnetic moment.
- Magnetisation $\vec{M}$ is the net magnetic dipole moment per unit volume. It depends on the vector sum of the moments of all domains.

Step 1: Describe an unmagnetised specimen Even without an external field, the atomic moments within each domain point predominantly in the same direction. However, different domains point in different directions in an unmagnetised specimen. Their moments approximately cancel, so the specimen has little or no net magnetisation. Thus, an unmagnetised piece is not one in which all atomic magnetic moments vanish.

Step 2: Apply an external magnetic field Domains oriented favourably along the applied field grow at the expense of unfavourably oriented domains through movement of domain walls. Domain magnetisations can also rotate towards the field. The cancellation is reduced and the vector sum becomes large in the field direction. A relatively weak field can therefore produce a large magnetisation: this explains the strong magnetic response of a ferromagnet. At sufficiently strong fields, nearly all domain magnetisations align, giving magnetic saturation.



Domain moments before magnetisation and in a strongly magnetised specimen.

Step 3: Relate the domain picture to retention Some domain alignment can remain when the applied field is removed, allowing suitable ferromagnets to form permanent magnets. In the sketches, each arrow represents the common direction of many atomic moments in a domain.

Step 4: Conclusion Ferromagnets such as iron are strongly magnetised along an applied field because their pre-existing magnetic domains grow and reorient to give a large resultant magnetic moment.

Quick Tip to Solve: Draw several domains: vary arrow directions before magnetisation and align them with the applied field afterwards; arrows within any one domain represent parallel atomic moments.

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 donor atom supplies five valence electrons. Four form covalent bonds with neighbouring Ge atoms, leaving one weakly bound electron.
- The donor level lies just below the conduction band; its ionisation energy is much smaller than the band gap of the host semiconductor.

Step 1: Identify the required energy The question asks for freeing the donor's fifth electron, not for breaking a host covalent bond to excite an electron across the full forbidden gap. In germanium the donor ionisation energy is approximately 0.01 eV, small enough for thermal energy to ionise many donors at room temperature.

Step 2: Compare the printed alternatives The value 0.001 eV is too small for the standard approximate donor energy in Ge. The values 0.72 eV and 1.1 eV are of the order of the band gaps of Ge and Si, respectively, and refer to a different energy scale.

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

Quick Tip to Solve: Distinguish the tiny donor ionisation energy from the much larger energy gap of the semiconductor host.

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 a fixed temperature in thermal equilibrium, the mass action law is $n_e n_h = n_i^2$, where n_e , n_h and n_i are electron, hole and intrinsic carrier concentrations.
- All concentrations in this relation must use the same volume unit. Since $1 \text{ m}^3 = 10^6 \text{ cm}^3$, a concentration in cm^{-3} is multiplied by 10^6 to express it in m^{-3} .

Step 1: Apply the mass action law The printed values are $n_i = 2.0 \times 10^{10} \text{ cm}^{-3}$ and $n_h = 8 \times 10^3 \text{ cm}^{-3}$. Pentavalent doping makes electrons the majority carriers. Therefore,

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

Step 2: Convert to the unit used in the options Each cubic metre contains a million cubic centimetres, so

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

Options (A), (B) and (C) do not equal this value. In particular, merely changing the unit label without the factor 10^6 , or failing to square the intrinsic concentration, would give an incorrect result.

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

Quick Tip to Solve: Square the intrinsic concentration first, divide by the minority concentration, then convert from cubic centimetres to cubic metres.

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 carries a species from a region of higher concentration to a region of lower concentration, even without an applied electric field.
- Electrons are majority carriers in the n -region, whereas holes are majority carriers in the p -region

of a semiconductor junction.

Step 1: Follow the electron concentration gradient When the junction forms, the electron concentration is much greater on the n -side. Electrons therefore diffuse from the n -region into the p -region. Their negative charge does not reverse the direction of diffusion down their own concentration gradient.

Step 2: Follow the hole concentration gradient Holes are more concentrated on the p -side, so they diffuse from the p -region into the n -region. Option (A) reverses both directions. Options (B) and (D) incorrectly make both carrier species diffuse in the same direction; each species follows its own concentration gradient.

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

Quick Tip to Solve: For diffusion, locate where each carrier is the majority and draw its motion towards the opposite region.

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 arises from the concentration gradients of electrons and holes across the junction.
- Drift current is driven by the electric field of the depletion layer and opposes diffusion current in an unbiased junction.

Step 1: Examine the initial concentration difference Immediately after the p - and n -regions form a junction, the majority-carrier concentration gradients are large. Electrons diffuse from n to p and holes from p to n , producing a large diffusion current.

Step 2: Examine the developing electric field Initially, the depletion layer and its barrier field have not fully developed, so drift current is small. As diffusion uncovers fixed ions, the barrier field grows and drift current increases. Eventually, in thermal equilibrium, the two currents have equal magnitudes and opposite directions. Thus (B) reverses the initial situation, (C) incorrectly assumes a large initial drift current, and (D) incorrectly assumes a small initial diffusion current.

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

Quick Tip to Solve: The word “initially” matters: concentration gradients exist first, while the depletion field builds up later.

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:

- A sinusoidal input has the form $V = V_0 \sin(\omega t)$, with angular frequency $\omega = 2\pi f$, where f is its frequency.
- A half-wave rectifier produces one output pulse per input cycle; a full-wave rectifier produces two output pulses per input cycle.

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

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

The amplitude 0.5 V does not affect this frequency.

Step 2: Count the output pulses Half-wave rectification retains only one half-cycle per input period, so the output repeats at 50 Hz. Full-wave rectification makes both half-cycles have the same polarity, so the output period halves and its frequency is $2f = 100 \text{ Hz}$. Options (A) and (B) incorrectly halve the half-wave frequency; option (C) misses the frequency doubling in full-wave rectification.

Step 3: Conclusion The respective output frequencies are 50 Hz and 100 Hz. Hence, the correct option is (D).

Quick Tip to Solve: Divide the coefficient of time in the sine by 2π , then use f for half-wave and $2f$ for full-wave output.

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 $P = 1/f$, with focal length f in metres and power P in dioptres.
- Powers of thin coaxial lenses in contact add algebraically: $P = P_1 + P_2$. A converging lens has positive power and a diverging lens has negative power.

Step 1: Assign signed focal lengths The converging lens has $f_1 = +0.20$ m, while the diverging lens has $f_2 = -0.15$ m. Thus their individual powers are +5 D and $-20/3$ D, respectively.

Step 2: Add the powers and compare the choices

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

The shorter focal length makes the diverging lens stronger, so the combined power must be negative. This rules out (C) and (D); (A) has the wrong magnitude. Adding focal lengths instead of powers is not valid for lenses in contact.

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

Quick Tip to Solve: Convert centimetres to metres and attach a minus sign to the diverging lens before adding powers.

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 refractive index of the lens material.
- For light travelling from left to right through a biconvex lens, choose $R_1 = +R$ and $R_2 = -2R$; the two convex surfaces have opposite signed radii.

Step 1: Substitute the signed radii The stated radii are magnitudes. Using their Cartesian signs gives

$$\frac{1}{f} = (\mu - 1) \left(\frac{1}{R} + \frac{1}{2R} \right) = \frac{3(\mu - 1)}{2R}.$$

Reversing the lens interchanges the magnitudes and gives the same sum of curvatures.

Step 2: Use the printed focal length The official question gives $f = 4R/3$. Therefore

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

Only option (C) satisfies this equation. The other three refractive indices fail the stated focal-length condition; treating both radii as positive also gives an incorrect curvature difference.

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

Quick Tip to Solve: For two convex faces, add the reciprocal radius magnitudes in the lens maker formula after assigning opposite signs.

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 of radius magnitude R in a surrounding medium has $f = R/[2(\mu_{\text{rel}} - 1)]$, where $\mu_{\text{rel}} = n_{\text{lens}}/n_{\text{medium}}$.
- For ordinary glass under normal dispersion, refractive index increases as the wavelength decreases. Cutting a lens along its principal axis reduces its aperture but preserves surface curvature.

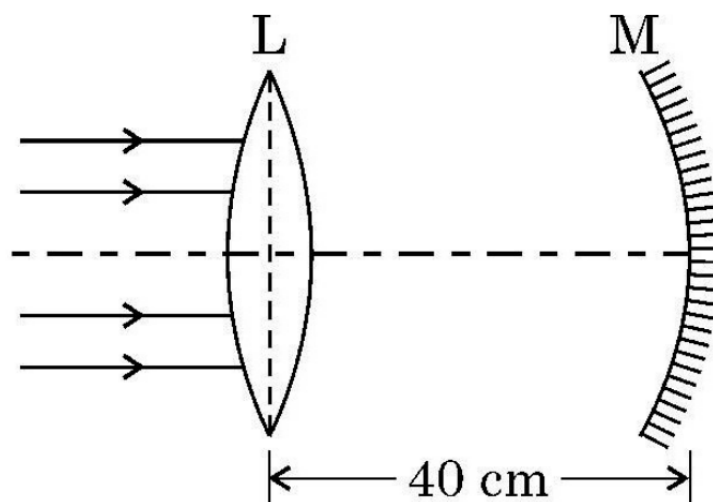
Step 1: Check immersion in water Replacing air by water raises the surrounding refractive index. For an ordinary glass lens, μ_{rel} decreases while remaining greater than one. The denominator of the focal-length formula therefore decreases, so the positive focal length increases. This supports (A).

Step 2: Test the remaining changes For (B), shorter wavelength raises the lens refractive index in normal dispersion, increasing power and decreasing focal length. For (C), reducing R reduces f directly. For (D), an axial cut leaves both curved surface radii unchanged; the focal length remains unchanged, although the smaller aperture collects less light. None of these three alternatives states the correct change.

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

Quick Tip to Solve: Separate curvature from refractive contrast: immersion changes relative index, while an axial cut changes aperture alone.

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 describes the final image after the reflected light passes back through the lens: it is at infinity. Option (B) is the intermediate image formed by the mirror.

Solution:

Concept:

- Parallel rays incident on a convex lens meet at its focus, a distance f_L beyond the lens.
- A concave mirror images an object at its centre of curvature back at that point. On return, rays emerging from the focus of a convex lens leave the lens parallel.

Step 1: Locate the first lens image Place the lens at $x = 0$ and the mirror at $x = 40$ cm. The incoming parallel beam focuses at $x = 10$ cm, then diverges towards the mirror. This point is $40 - 10 = 30$ cm in front of the mirror, exactly its radius of curvature $2f_M = 30$ cm.

Step 2: Find the intermediate mirror image With the mirror's Cartesian signs, $u_M = -30$ cm and $f_M = -15$ cm. Thus

$$\frac{1}{v_M} = \frac{1}{f_M} - \frac{1}{u_M} = -\frac{1}{15} + \frac{1}{30} = -\frac{1}{30}.$$

The mirror image is 30 cm in front of the mirror, at $x = 10$ cm. This is 10 cm right of the lens, the position in option (B).

Step 3: Account for the return passage through the lens After meeting at this intermediate image, the reflected rays continue leftwards and encounter the lens again. Taking leftwards as the positive propagation direction for this pass, $u'_L = -10$ cm, $f_L = +10$ cm, and

$$\frac{1}{v'_L} = \frac{1}{f_L} - \frac{1}{u'_L} = \frac{1}{10} - \frac{1}{10} = 0.$$

The emerging beam is parallel. None of the four finite image distances describes this final outgoing beam; (A), (C) and (D) do not even give the intermediate mirror image. Option (B) applies only if

the question intends the image before the return through the lens.

Step 4: Conclusion For the complete lens–mirror system the final image is at infinity, so no printed option is correct. The intermediate mirror image is 10 cm right of the lens, corresponding to (B) under that restricted interpretation.

Quick Tip to Solve: Trace the entire path: lens, mirror, then lens again. A mirror image at the lens focus produces a parallel final beam.

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:

- Parallel incident rays form an image at the second principal focus of a convex lens.
- For the next lens, use $1/v - 1/u = 1/f$, with distances measured from that lens. A real object on the incident side has $u < 0$.

Step 1: Locate the object for the second lens Lens L_1 focuses the parallel beam 16 cm to its right. Lens L_2 is 40 cm to its right, so the first image lies $40 - 16 = 24$ cm to the left of L_2 . It acts as a real object for L_2 : $u_2 = -24$ cm.

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

$$\frac{1}{v_2} = \frac{1}{12} - \frac{1}{24} = \frac{1}{24}, \quad v_2 = +24 \text{ cm.}$$

Positive image distance means a real image on the outgoing side. Thus the virtual-image choices (B) and (D) fail, and (C) has the wrong distance. The object is at $2f_2$, which also confirms an image at $2f_2$.

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

Quick Tip to Solve: First subtract the first focal length from the lens separation; here this gives exactly twice the second focal length.

Section E (15 marks)

31(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?

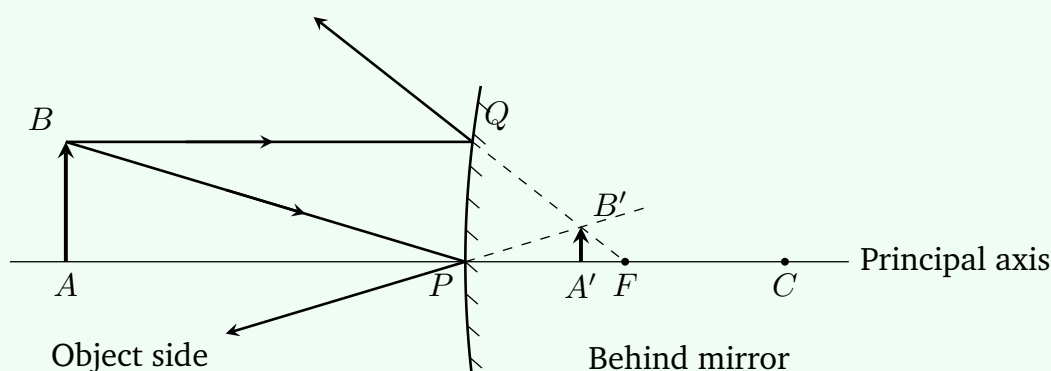
(iii) The magnification of a small object produced by a compound microscope is 200. The focal length of the eyepiece is 2 cm and the final image is formed at infinity. Find the magnification produced by the objective. [5 marks]

Solution:

Concept:

- A convex mirror diverges reflected rays; their backward extensions meet behind the mirror to form a virtual, erect and diminished image.
- The paraxial mirror formula uses Cartesian distances from the pole: object distance $u < 0$, virtual-image distance $v > 0$ and convex-mirror focal length $f > 0$.
- For a compound microscope adjusted for a relaxed eye, the magnification magnitude is $M = |m_o|D/f_e$, where m_o is the objective's linear magnification, f_e is the eyepiece focal length and $D = 25$ cm.

Step 1: (i) Construct the image with two principal rays Let AB be the object, P the pole, F the principal focus and C the centre of curvature. A ray from B , parallel to the principal axis, strikes the mirror at Q and reflects as if it came from F . A second ray from B strikes P and reflects with equal angles to the principal axis, the normal at P . Extend these reflected rays backwards with dashed lines: they meet at B' , with A' on the axis. Thus $A'B'$ lies between P and F . The diagram is schematic; the derivation uses rays close to the principal axis.



Convex-mirror image formation: solid lines are real rays and dashed lines are backward extensions. The mirror sag is neglected in the paraxial derivation.

Step 2: (i) Derive the mirror equation from similar triangles Write the positive lengths $AP = a$, $PA' = b$, $PF = f$, $AB = h$ and $A'B' = h'$. From the ray reflected at the pole, the right triangles ABP and $A'B'P$ are similar, so

$$\frac{h'}{h} = \frac{b}{a}.$$

For a mirror of small aperture, the point Q may be taken in the transverse plane through P , giving $PQ \simeq h$. The backward extension of the parallel ray passes through F ; triangles $A'B'F$ and PQF

therefore give

$$\frac{h'}{h} = \frac{FA'}{FP} = \frac{f-b}{f}.$$

Equating the ratios and rearranging,

$$\begin{aligned}\frac{b}{a} &= 1 - \frac{b}{f}, \\ \frac{1}{a} &= \frac{1}{b} - \frac{1}{f}, \\ \frac{1}{f} &= \frac{1}{b} - \frac{1}{a}.\end{aligned}$$

In the Cartesian convention, $u = -a$ and $v = b$. Substitution gives the required signed mirror relation $1/f = 1/v + 1/u$. Keeping the negative sign of u is essential even though the geometric lengths used above were positive.

Step 3: (ii) Explain why the lenses have several components A single lens has chromatic aberration because its refractive index, and therefore its focal length, depend on wavelength. It also has spherical aberration: rays entering at different distances from the axis do not all focus at the same point. Carefully combining lens elements of suitable glasses, curvatures and powers reduces these aberrations. Multi-component objectives and eyepieces therefore produce sharper images with much smaller coloured fringes and less distortion than simple lenses.

Step 4: (iii) Separate the objective and eyepiece magnifications The final image is at infinity, so the intermediate image made by the objective is at the first focal plane of the eyepiece. The eyepiece's angular magnification for this normal adjustment is

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

The total magnification magnitude is the product of the objective's linear magnification magnitude and the eyepiece's angular magnification. Hence

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

The objective forms a real, inverted intermediate image; its signed linear magnification is therefore negative. The formula $1 + D/f_e$ would apply to a final image at the near point and is not the appropriate eyepiece factor here.

Step 5: Conclusion (i) The convex mirror gives a virtual, erect, diminished image and obeys $1/f = 1/v + 1/u$. (ii) Multi-component lenses reduce chromatic and spherical aberrations, improving image sharpness. (iii) The objective magnifies the object $\boxed{16}$ times; its signed magnification is $m_o = -16$.

Quick Tip to Solve: Derive mirror relations using positive geometric lengths first, then put $u = -a$. For a microscope with the final image at infinity, divide total magnification by D/f_e .

31(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]

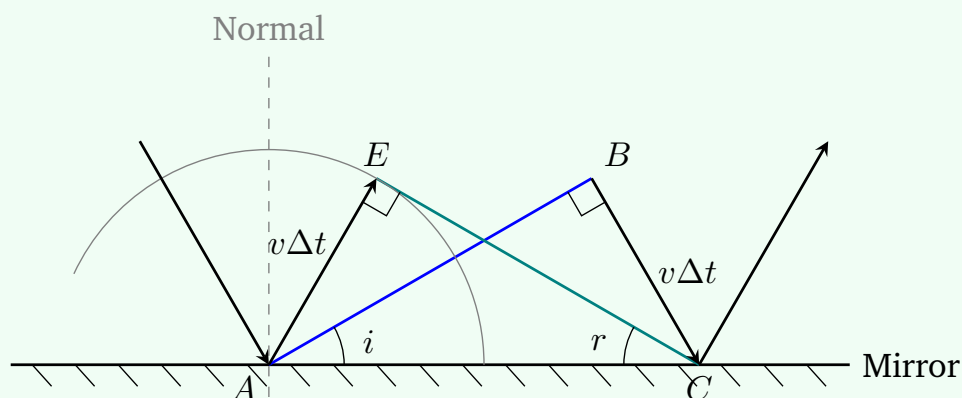
Solution:

Concept:

- A wavefront is a surface joining points in the same phase. A ray gives the local direction of propagation and is normal to the wavefront in an isotropic medium.
- Huygens' construction treats each wavefront point as a source of secondary wavelets; the forward envelope after time Δt is the new wavefront.
- In Young's experiment, fringe width is $\beta = \lambda D/d$. Bright fringes occur at $y_n = n\beta$, and dark fringes at $y_n = (n - \frac{1}{2})\beta$, measured from the central bright fringe on either side.

Step 1: (i) Distinguish a wavefront from a ray A wavefront represents equal phase over a surface, such as a sphere around a point source or a plane for a parallel beam. A ray is a directed line showing the propagation of light energy. Thus a wavefront describes the spatial phase distribution, whereas a ray describes propagation direction. In a homogeneous isotropic medium, rays are perpendicular to wavefronts; a plane wavefront has parallel rays.

Step 2: (ii) Apply Huygens' principle at the reflecting surface Every point on a wavefront acts as a source of secondary spherical wavelets that travel with the speed of light in the medium. The common forward tangent surface to these wavelets gives the wavefront at a later instant. Let the plane incident wavefront AB meet the plane mirror first at A . During time Δt , the disturbance at B reaches C , so $BC = v\Delta t$. In the same time, the reflected secondary wavelet centred at A has radius $AE = v\Delta t$. Draw the tangent CE from C to that wavelet. This is the reflected wavefront, with $AE \perp CE$; incident propagation gives $BC \perp AB$.



Huygens' reflection construction: AB is incident, EC reflected, and $AE = BC$. Angles with the mirror equal the corresponding ray angles with the normal.

Step 3: Prove both laws of reflection Triangles ABC and AEC are right-angled at B and E . They have the common hypotenuse AC , and $BC = AE = v\Delta t$. Therefore they are congruent by the right-angle-hypotenuse-side criterion, giving

$$\angle BAC = \angle ECA.$$

Since the rays are normal to their wavefronts, the angle between AB and the mirror equals the angle of incidence i ; similarly, the angle between CE and the mirror equals the angle of reflection r . Thus $i = r$. The construction is made in the plane containing the incident ray and the surface normal. The reflected ray, perpendicular to CE , also lies in this plane. Hence the incident ray, reflected ray and normal at the point of incidence are coplanar, verifying the second law.

Step 4: (iii) Determine the fringe width and wavelength For the usual interpretation that the two fringes are on the same side of the central maximum, the fourth bright fringe is at 4β and the second dark fringe is at $3\beta/2$. Their separation gives

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

Substitute $D = 1.0 \text{ m}$, $d = 3 \times 10^{-3} \text{ m}$, and $\beta = 2 \times 10^{-3} \text{ m}$:

$$\lambda = \frac{\beta d}{D} = \frac{(2 \times 10^{-3})(3 \times 10^{-3})}{1.0} \text{ m} = 6.0 \times 10^{-6} \text{ m}.$$

The wording does not explicitly specify the side. If the fringes were on opposite sides, their separation would instead be $(4 + 3/2)\beta$, giving $\lambda = (30/11) \times 10^{-6} \text{ m}$. The standard same-side interpretation yields the value above.

Step 5: Conclusion A wavefront is an equal-phase surface; a ray is its propagation normal. Huygens' construction establishes $i = r$ and coplanarity of the rays and normal. The wavelength is $6.0 \times 10^{-6} \text{ m}$ under the usual same-side interpretation.

Quick Tip to Solve: Count the central maximum as order zero: the fourth bright fringe is at 4β , but the second dark fringe is at 1.5β . Subtract these positions only when both are on the same side.

32(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.
- With free surface charge density $\sigma = Q/A$, the fields normal to wide parallel plates are $E_0 = \sigma/\epsilon_0$ in air and $E_K = \sigma/(K\epsilon_0)$ inside a linear dielectric of relative permittivity K , neglecting edge effects.
- The stored energy at applied voltage V is $U = \frac{1}{2}C_{\text{eq}}V^2$. Two capacitors obey $C_s = C_1C_2/(C_1 + C_2)$ in series and $C_p = C_1 + C_2$ in parallel.

Step 1: (i) Add the voltage drops across air and dielectric Assume the slab fills the full plate area A , has thickness $t \leq d$, and is parallel to the plates. The total thickness of the remaining air gap or gaps is $d - t$. Let the free charge on the plates be $+Q$ and $-Q$. Since there is no free charge at an

air–dielectric interface, the normal electric displacement is the same in both regions. Consequently,

$$E_0 = \frac{Q}{\varepsilon_0 A}, \quad E_K = \frac{Q}{K \varepsilon_0 A}.$$

Add the potential drops through the two media:

$$\begin{aligned} V &= E_0(d - t) + E_K t \\ &= \frac{Q}{\varepsilon_0 A} \left(d - t + \frac{t}{K} \right). \end{aligned}$$

Step 2: Obtain the capacitance and check limiting cases By definition, the required capacitance is

$$C = \frac{Q}{V} = \frac{\varepsilon_0 A}{d - t + t/K} = \frac{K \varepsilon_0 A}{K(d - t) + t}.$$

This expression is independent of the slab's position between the plates because only the total air thickness matters. If $t = 0$, it reduces to the air capacitor value $\varepsilon_0 A/d$. If $t = d$, the gap is entirely dielectric and $C = K \varepsilon_0 A/d$. For $K > 1$, inserting the slab increases capacitance by reducing the effective separation $d - t + t/K$.

Step 3: (ii) Infer the equivalent capacitances from the energies The source maintains $V = 100 \text{ V}$ across each complete combination. Use $C_{\text{eq}} = 2U/V^2$, converting millijoules to joules:

$$\begin{aligned} C_s &= \frac{2(40 \times 10^{-3})}{100^2} \text{ F} = 8.0 \times 10^{-6} \text{ F} = 8.0 \mu\text{F}, \\ C_p &= \frac{2(250 \times 10^{-3})}{100^2} \text{ F} = 50 \times 10^{-6} \text{ F} = 50 \mu\text{F}. \end{aligned}$$

In series, the voltage divides between the capacitors; the full 100 V belongs across the equivalent combination. In parallel, both capacitors individually have the source voltage.

Step 4: Solve for the two individual capacitances Let the numerical capacitances in μF be c_1 and c_2 . The parallel and series relations give

$$c_1 + c_2 = 50, \quad \frac{c_1 c_2}{c_1 + c_2} = 8, \quad c_1 c_2 = 400.$$

Each value is therefore a root of

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

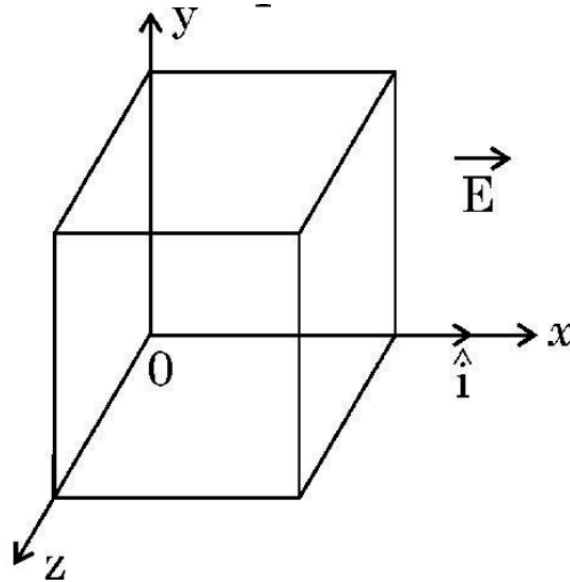
As a check, these roots have sum 50, while their product divided by their sum is $400/50 = 8$, agreeing with the energy-derived equivalent capacitances.

Step 5: Conclusion The slab-loaded capacitance is $C = \varepsilon_0 A/(d - t + t/K)$. The individual capacitors have capacitances $10 \mu\text{F}$ and $40 \mu\text{F}$, in either order.

Quick Tip to Solve: First convert each stored energy into an equivalent capacitance using $2U/V^2$. The parallel value gives the sum of the two capacitances; multiply it by the series value to obtain their product.

32(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 a closed surface.
- An infinite uniformly charged plane has translational symmetry along the plane and reflection symmetry across it. Its electric field is normal to the sheet, with equal magnitude at equal distances on its two sides.
- Electric flux through a face with uniform field is $\Phi = \vec{E} \cdot \vec{A}$. For a field directed along x , only faces normal to the x -axis contribute to a cube's net flux.

Step 1: (i) Choose a Gaussian pillbox Let the infinite sheet have uniform surface charge density σ . Symmetry eliminates any component of field parallel to the sheet: there is no preferred direction in its plane. Choose a short cylindrical Gaussian surface whose axis is perpendicular to the sheet, with equal end areas A on opposite sides at equal distances. The sheet cuts across the cylinder between its ends, so the enclosed charge is $Q_{\text{enc}} = \sigma A$. For a positive sheet, the field points away from it on both sides.

Step 2: (i) Evaluate the flux and apply Gauss's law On the curved surface, the field is tangent to the surface and perpendicular to its outward area vector, so the flux is zero. On each plane end, the field is parallel to the outward normal and has uniform magnitude E ; hence each end contributes EA . Therefore,

$$\begin{aligned}\oint \vec{E} \cdot d\vec{A} &= EA + EA = 2EA, \\ 2EA &= \frac{\sigma A}{\epsilon_0}, \\ E &= \frac{\sigma}{2\epsilon_0}.\end{aligned}$$

Taking $\hat{n}$ as the unit normal directed from the sheet toward the observation point gives $\vec{E} = (\sigma/2\epsilon_0)\hat{n}$. This vector expression also covers a negative σ , for which the field is toward the sheet. Neither the area nor the distance from the ideal infinite sheet appears in the result.

Step 3: (ii)(1) Identify the contributing cube faces In the printed figure, the origin is at a vertex and the cube extends along the positive coordinate directions. Its side is $a = 10 \text{ cm} = 0.10 \text{ m}$. The faces perpendicular to the x -axis are at $x = 0$ and $x = a$, each of area $a^2 = 0.010 \text{ m}^2$. Since $\vec{E} = (5x^2 + 2)\hat{i}$, it is tangent to the other four faces and their flux is zero. The outward normals on the two contributing faces are $-\hat{i}$ and $+\hat{i}$, respectively.

Step 4: (ii)(1) Subtract incoming flux from outgoing flux The field is constant over each face because every point of that face has the same x -coordinate. At the left face, $E(0) = 2 \text{ N/C}$; at the right face, $E(a) = 5(0.10)^2 + 2 = 2.05 \text{ N/C}$. Thus,

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

The uniform term $2\hat{i}$ contributes equal incoming and outgoing flux and therefore cancels. The positive net flux arises from the increase in field along x .

Step 5: (ii)(2) Obtain the enclosed charge Gauss's law relates the net outward flux to the total charge inside the cube, regardless of the distribution of that charge. Using $\epsilon_0 = 8.854 \times 10^{-12} \text{ C}^2/(\text{N m}^2)$,

$$\begin{aligned}Q_{\text{enc}} &= \epsilon_0 \Phi_{\text{net}} \\ &= (8.854 \times 10^{-12})(5.0 \times 10^{-4}) \\ &= 4.427 \times 10^{-15} \text{ C}.\end{aligned}$$

Its sign is positive, consistently with the outward flux exceeding the inward flux.

Step 6: Conclusion (i) The field is $\vec{E} = \frac{\sigma}{2\epsilon_0}\hat{n}$, normal to the sheet and independent of distance. (ii) The cube's net outward flux is $5.0 \times 10^{-4} \text{ N m}^2/\text{C}$, and its enclosed charge is approximately $+4.43 \times 10^{-15} \text{ C}$.

Quick Tip to Solve: For a cube aligned with a field $E_x(x)\hat{i}$, use $\Phi = [E_x(x_{\text{right}}) - E_x(x_{\text{left}})]a^2$. Convert the side to metres before evaluating the field or area.

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, $Z = \sqrt{R^2 + (\omega L - 1/\omega C)^2}$, where R , L and C are the resistance, inductance and capacitance, and $\omega = 2\pi f$.
- Resonance occurs when the inductive and capacitive reactances cancel: $X_L = X_C$. The impedance

then has its minimum value R .

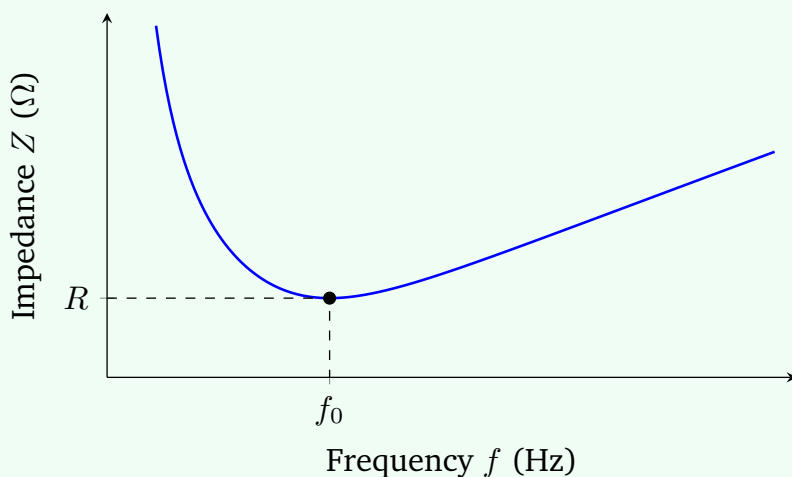
- A transformer works by mutual induction: changing magnetic flux Φ linking each turn produces an emf $e = -N d\Phi/dt$ in a coil of N turns.

Step 1: (i) Identify the factors controlling resonance At resonance, the net reactance is zero. Therefore,

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

Thus the resonant frequency depends on the inductance L and capacitance C , and is independent of the series resistance R for this ideal LCR model. Increasing either L or C decreases f_0 . Resistance determines the minimum impedance and sharpness of resonance, rather than its frequency.

Step 2: (i) Plot impedance against applied frequency At very low frequency the capacitive reactance is large, so the impedance is large. As frequency rises towards f_0 , the difference between the reactances decreases and Z falls. At $f = f_0$, the reactances cancel and $Z = R$. Above f_0 , inductive reactance dominates and Z increases again. The following schematic curve shows a nonzero minimum for $R > 0$; it is an impedance minimum, not a current minimum.



Impedance is minimum at resonance (schematic axes).

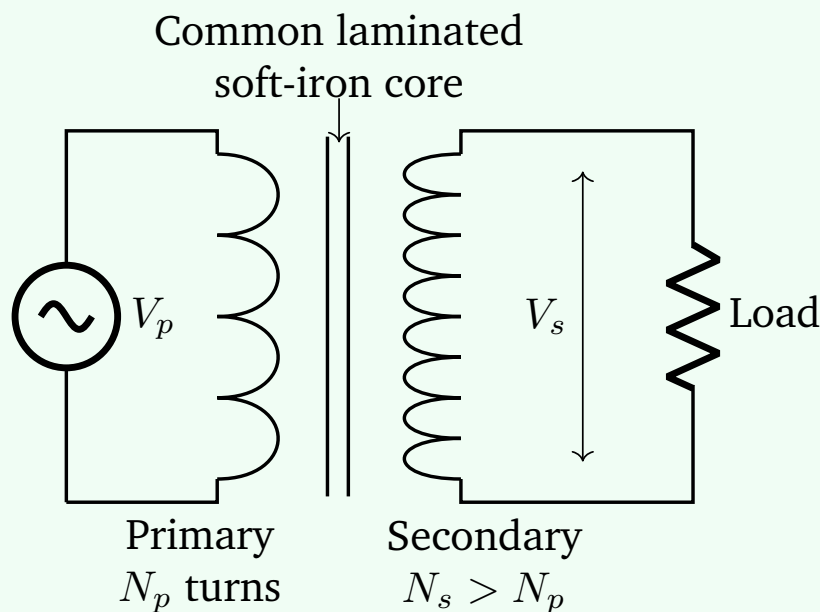
Step 3: (ii) Explain the construction and operation of a step-up transformer Two insulated coils, the primary with N_p turns and the secondary with N_s turns, are wound on a common laminated soft-iron core. For a step-up transformer, $N_s > N_p$. The diagram uses the standard coupled-coil symbol; the parallel lines represent the common iron core. An alternating voltage applied to the primary produces an alternating current and hence a changing magnetic flux in the core. This flux links the secondary and induces an alternating emf in it by mutual induction. The coils are electrically isolated; energy is transferred through the common varying magnetic field. With negligible leakage, the same flux links every turn, so

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

For an ideal transformer, the ratio of rms terminal voltages is

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

The secondary therefore supplies a higher alternating voltage. Ideally, $V_p I_p = V_s I_s$, giving $I_s/I_p = N_p/N_s < 1$: the voltage increase is accompanied by a current decrease. A steady direct voltage cannot sustain the changing core flux required for transformer action.



Step-up transformer: more secondary turns give a higher a.c. voltage.

Step 4: (iii) State two causes of energy loss **Copper loss:** The primary and secondary windings have finite resistances, so current heats them. The total resistive loss is $I_p^2 R_p + I_s^2 R_s$, where the currents are rms values.

Eddy-current loss: The changing magnetic flux induces circulating currents within the conducting iron core. These currents dissipate energy as heat. Using thin insulated laminations increases the resistance of the circulating-current paths and reduces this loss.

Step 5: Conclusion The resonant frequency is $f_0 = 1/(2\pi\sqrt{LC})$, set by L and C , with minimum impedance $Z = R$. A step-up transformer uses mutual induction and $N_s > N_p$ to give $V_s > V_p$. Two real-transformer losses are winding-resistance heating and eddy-current heating in the core.

Quick Tip to Solve: Put the minimum of the impedance curve at (f_0, R) . For a step-up transformer, draw more secondary turns and use the turns ratio for voltage; the current ratio is its reciprocal.

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]

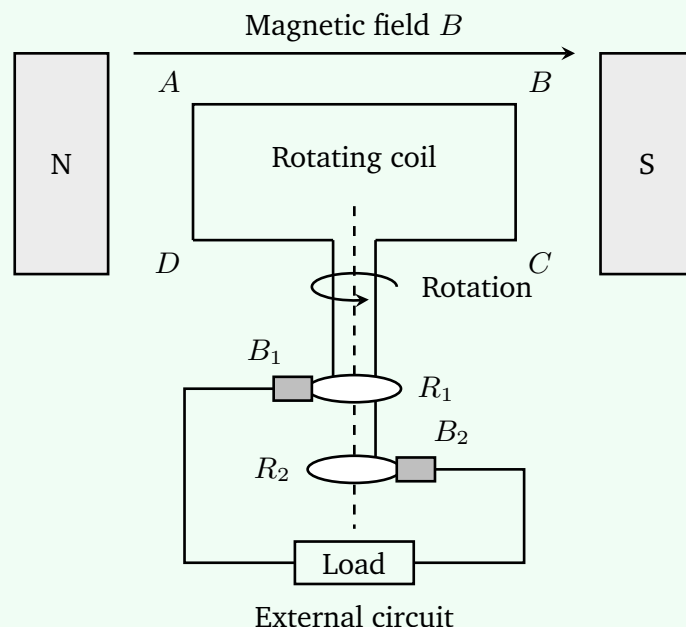
Solution:

Concept:

- An ac generator works on electromagnetic induction: the induced emf is $\mathcal{E} = -d(N\Phi)/dt$, where $N\Phi$ is the magnetic flux linkage of its rotating coil.
- A charge completing a circular orbit in period T is equivalent to a current of magnitude $I = e/T$. The magnetic dipole moment has magnitude $\mu = IA$, where A is the enclosed area and e is the magnitude of the electron charge.

Step 1: (i) Describe the construction of the ac generator A rectangular armature coil $ABCD$, of N

insulated turns and area A , rotates between the north and south poles of a strong magnet. Its axle is perpendicular to the magnetic field. The two coil ends are connected to separate, mutually insulated conducting slip rings R_1 and R_2 , which rotate with the axle. Stationary carbon brushes B_1 and B_2 press against the rings and connect the coil to an external load. A mechanical source rotates the axle. The schematic shows the coil at one instant; the rings maintain electrical contact throughout its rotation.



Schematic ac generator: rotating armature, separate slip rings, stationary brushes and load.

Step 2: (i) Explain the working and the alternating output As the coil rotates, its flux linkage changes and an emf is induced. Let its angular speed be ω , and let its area normal initially be parallel to the uniform field B . After time t , the angle between the normal and the field is $\theta = \omega t$, giving

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

Thus the peak emf is $\mathcal{E}_0 = NBA\omega$. After each half-revolution, the motion of each active side relative to the field reverses and the emf changes sign. Current therefore alternates in the external load; for a resistive load of total circuit resistance R , $I = \mathcal{E}/R$. Slip rings preserve each coil-end connection, allowing this reversal to reach the load. The generator converts mechanical energy into electrical energy; the induced current opposes the driving rotation in accordance with Lenz's law.

Step 3: (ii) Find the equivalent current of the orbiting electron The electron travels a distance $2\pi r$ in one revolution, so its orbital period and the magnitude of the equivalent current are

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

Conventional current circulates opposite to the electron's motion because the electron has charge $-e$. The proton at the centre does not contribute to this orbital current in the stated model.

Step 4: (ii) Multiply the current by the orbital area The circular orbit encloses area $A = \pi r^2$. Hence its magnetic moment has magnitude

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

Its direction is perpendicular to the orbital plane, given by the right-hand rule for conventional current. It is opposite to the electron's orbital angular momentum $\vec{L}$. Since $L = m_e v r$, the vector relation is $\vec{\mu} = -e\vec{L}/(2m_e)$. This sign expresses the negative charge; the magnitude $evr/2$ is positive and has SI unit A m^2 .

Step 5: Conclusion (i) A rotating coil with slip rings and brushes produces $\mathcal{E} = NBA\omega \sin \omega t$, reversing polarity every half-turn. (ii) The electron's orbital magnetic moment is $\mu = evr/2$, directed opposite to its orbital angular momentum.

Quick Tip to Solve: For the generator, measure the flux angle from the coil's normal. For an orbiting electron, use $I = e/T$ and reverse the electron's direction when applying the current-loop right-hand rule.