

CBSE Class 12 Physics Question Paper 2025 with Solution PDF-Set 55/5/2



Question Paper with Solutions

Conducted by the Central Board of Secondary Education (CBSE)

Time Allowed: 3 hours

Maximum Marks: 70

General Instructions

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

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

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

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

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

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

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

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

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

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

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

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

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

Section A (16 marks)

1. Which of the following rays coming from the Sun plays an important role in maintaining the Earth's warmth? [1 mark]

- (A) Infrared rays
- (B) γ rays
- (C) UV rays
- (D) Visible light rays

Correct Answer: (A) Infrared rays

Solution:

Concept:

- Infrared radiation is associated with the heating effect of electromagnetic waves: absorbed radiation transfers energy to matter.
- The Earth's temperature depends on the balance between absorbed solar energy and emitted thermal radiation, much of which lies in the infrared region.

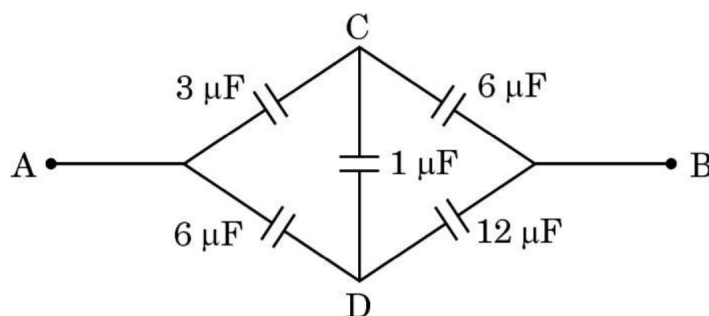
Step 1: Identify the radiation associated with warmth Solar infrared radiation is absorbed by matter and increases its internal energy. Infrared rays are therefore conventionally called heat rays and play an important role in maintaining the Earth's warmth.

Step 2: Compare the alternatives Gamma rays and ultraviolet rays are higher-frequency radiation associated primarily with ionising or photochemical effects. Visible sunlight also supplies energy, but the spectral region specifically associated with thermal radiation and the heating effect asked here is infrared.

Step 3: Conclusion Infrared rays play the stated role in maintaining the Earth's warmth. Hence, the correct option is (A).

Quick Tip to Solve: Link thermal radiation and the familiar phrase "heat rays" with the infrared region of the electromagnetic spectrum.

2. The effective capacitance of the network between points A and B shown in the figure is: [1 mark]



(A) $\frac{4}{3} \mu\text{F}$

(B) $2 \mu\text{F}$

(C) $\frac{3}{2} \mu\text{F}$

(D) $6 \mu\text{F}$

Correct Answer: (D) $6 \mu\text{F}$

Solution:

Concept:

- Capacitors in series have equivalent capacitance $C_s = C_1 C_2 / (C_1 + C_2)$; capacitances in parallel add.
- A balanced capacitive bridge has equal midpoint potentials, so the capacitor connecting those midpoints has zero potential difference and carries no charge.

Step 1: Check the bridge balance The upper arm contains $3 \mu\text{F}$ and $6 \mu\text{F}$, while the lower arm contains $6 \mu\text{F}$ and $12 \mu\text{F}$. Their ratios are equal: $3/6 = 6/12$. Thus $V_C = V_D$; the central $1 \mu\text{F}$ capacitor does not affect the equivalent capacitance.

Step 2: Combine the two active branches Each arm is a series combination, and the two arms are connected in parallel between A and B:

$$C_{\text{upper}} = \frac{3 \times 6}{3 + 6} = 2 \mu\text{F}, \quad C_{\text{lower}} = \frac{6 \times 12}{6 + 12} = 4 \mu\text{F}.$$

Hence the total is $2 + 4 = 6 \mu\text{F}$. Option (B) counts only the upper arm; (A) incorrectly combines the two arm equivalents in series; (C) is also inconsistent with the parallel connection.

Step 3: Conclusion The effective capacitance is $6 \mu\text{F}$. Hence, the correct option is (D).

Quick Tip to Solve: Check $3/6 = 6/12$ before combining capacitors: equal arm ratios let you omit the central bridge capacitor.

3. The electric field at a point in a region is given by $\vec{E} = \frac{\alpha}{r^3} \vec{r}$, where α is a constant and r is the distance of the point from the origin. The magnitude of potential of the point is: [1 mark]

- (A) $\frac{\alpha}{r}$
(B) $\frac{\alpha r^2}{2}$
(C) $\frac{\alpha}{2r^2}$
(D) $-\frac{\alpha}{r}$

Correct Answer: (A) $\frac{\alpha}{r}$

Solution:

Concept:

- For a radial electric field, $E_r = -dV/dr$, where V is the electric potential and r is the radial distance.
- The position vector has magnitude r , so $\vec{E} = (\alpha/r^3)\vec{r} = (\alpha/r^2)\hat{r}$.

Step 1: Extract the radial field The extra factor r in the position vector cancels one power of r in the denominator. Thus the radial component is α/r^2 , not α/r^3 .

Step 2: Integrate using zero potential at infinity Taking the usual reference $V(\infty) = 0$,

$$V(r) = - \int_{\infty}^r \frac{\alpha}{s^2} ds = \frac{\alpha}{r}.$$

Its magnitude is $|\alpha|/r$, represented by α/r in the printed options with the usual positive-constant convention. Option (B) has the wrong radial dependence; (C) incorrectly treats the vector expression as a scalar inverse-cube field; (D) reverses the integration sign and gives a negative value for positive α .

Step 3: Conclusion With zero potential at infinity, the required potential magnitude corresponds to α/r . Hence, the correct option is (A).

Quick Tip to Solve: First replace $\vec{r}$ by $r\hat{r}$; integrate the resulting inverse-square radial field only after this simplification.

4. Two coherent light waves, each having amplitude a , superpose to produce an interference pattern on a screen. The intensity of light as seen on the screen varies between: [1 mark]

- (A) 0 and $2a^2$
(B) 0 and $4a^2$
(C) a^2 and $2a^2$
(D) $2a^2$ and $4a^2$

Correct Answer: (B) 0 and $4a^2$

Solution:

Concept:

- The resultant intensity for two coherent waves is $I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \phi$, where ϕ is their phase difference.

- Intensity is proportional to the square of amplitude. In the units used by the options, each wave of amplitude a has intensity a^2 .

Step 1: Express the intensity at any point For equal amplitudes, put $I_1 = I_2 = a^2$. The interference term depends on position through the phase difference:

$$I = 2a^2(1 + \cos \phi).$$

Step 2: Evaluate destructive and constructive interference At a dark fringe, $\cos \phi = -1$, giving $I_{\min} = 0$. At a bright fringe, $\cos \phi = 1$, giving $I_{\max} = 4a^2$. The value $2a^2$ is the sum of the individual intensities, not the maximum coherent intensity. Thus option (A) gives the wrong maximum, while (C) and (D) incorrectly exclude complete destructive interference.

Step 3: Conclusion The intensity varies from 0 to $4a^2$. Hence, the correct option is (B).

Quick Tip to Solve: For equal amplitudes, square their difference and their sum: $(a-a)^2 = 0$ and $(a+a)^2 = 4a^2$.

5. A current of $\left(\frac{10}{\pi}\right)$ A is maintained in a circular loop of radius 14 cm. The value of dipole moment associated with the loop is: [1 mark]

- (A) 0.019 Am^2
- (B) 0.14 Am^2
- (C) 0.196 Am^2
- (D) 0.615 Am^2

Correct Answer: (C) 0.196 Am^2

Solution:

Concept:

- The magnitude of the magnetic dipole moment of a plane current loop is $m = IA$, where I is current and A is the enclosed area.
- For a circular loop of radius r , $A = \pi r^2$. The SI unit of magnetic dipole moment is Am^2 .

Step 1: Convert the radius to SI units The radius is $14 \text{ cm} = 0.14 \text{ m}$, and the current is $I = 10/\pi \text{ A}$. Since the moment contains area, the converted radius must be squared.

Step 2: Multiply the current by the circular area For this single loop,

$$m = \frac{10}{\pi} \times \pi(0.14)^2 = 10 \times 0.0196 = 0.196 \text{ Am}^2.$$

The factors of π cancel. Option (D) effectively retains an extra factor of π ; (B) resembles the radius rather than current times area, and (A) is about ten times too small.

Step 3: Conclusion The magnetic dipole moment has magnitude 0.196 Am^2 . Hence, the correct option is (C).

Quick Tip to Solve: Cancel the π in $I\pi r^2$ first, but convert 14 cm to 0.14 m before squaring.

6. A transformer is a device used for converting:

[1 mark]

- (A) high ac voltage and large ac current to low ac voltage and small ac current
- (B) high ac voltage and small ac current to low ac voltage and small ac current
- (C) low ac voltage and large ac current to high ac voltage and small ac current
- (D) low ac voltage and small ac current to high ac voltage and large ac current

Correct Answer: (C) low ac voltage and large ac current to high ac voltage and small ac current

Solution:

Concept:

- A transformer changes alternating voltage through mutual induction between its primary and secondary coils.
- For an ideal transformer, $V_s/V_p = N_s/N_p$ and $V_p I_p = V_s I_s$, where N , V and I denote turns, rms voltage and rms current.

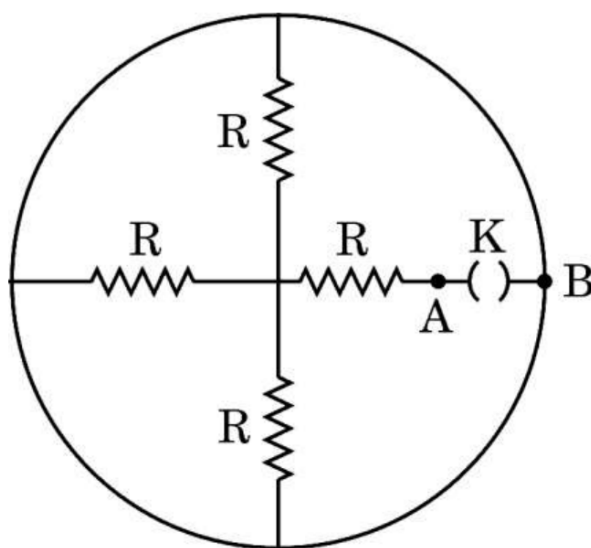
Step 1: Apply conservation of power Increasing the secondary voltage requires a corresponding decrease in secondary current for a given transferred power. A step-up transformer therefore converts low ac voltage and large ac current into high ac voltage and small ac current.

Step 2: Check the other conversions Option (A) decreases both voltage and current, and (D) increases both; neither describes the normal ideal-transformer relation. In (B), stepping the voltage down should increase the current, rather than retain a small current as stated. Option (C) alone correctly pairs a voltage increase with a current decrease.

Step 3: Conclusion A transformer can convert low ac voltage and large ac current to high ac voltage and small ac current. Hence, the correct option is (C).

Quick Tip to Solve: Use VI approximately constant: whenever transformer voltage steps up, its current must step down.

7. Four resistors, each of resistance R and a key K are connected as shown in the figure. The equivalent resistance between points A and B when key K is open, will be: [1 mark]



- (A) $4R$
- (B) ∞
- (C) $\frac{R}{4}$
- (D) $\frac{4R}{3}$

Correct Answer: (D) $\frac{4R}{3}$

Solution:

Concept:

- Points joined by an ideal wire form one node at a common potential.
- Series resistances add; parallel resistances obey $1/R_p = \sum_i 1/R_i$. An open key removes only its own branch.

Step 1: Identify the common nodes Let O be the centre. The outer circular wire joins the upper, left and lower resistors to B . These three resistors connect O to B in parallel. The fourth connects A to O . Opening K removes the direct A – B wire but leaves the route through the resistors.

Step 2: Reduce the network The three equal resistors between O and B give

$$\frac{1}{R_p} = \frac{3}{R}, \quad R_p = \frac{R}{3}.$$

Adding the A – O resistor in series gives $R_{AB} = R + R/3$. Option (A) wrongly puts all four in series; (C) puts all four in parallel; (B) overlooks the remaining path through the resistors.

Step 3: Conclusion With K open, the equivalent resistance is $\frac{4R}{3}$. Hence, the correct option is (D).

Quick Tip to Solve: Treat the outer circle as node B : three radial resistors are parallel, with the A -side resistor in series.

8. Which of the following electromagnetic waves has photons of largest momentum?

[1 mark]

- (A) X-rays
- (B) AM radio waves
- (C) Microwaves
- (D) TV waves

Correct Answer: (A) X-rays

Solution:

Concept:

- A photon has momentum $p = h/\lambda = h\nu/c$, where h is Planck's constant, λ is wavelength and ν is frequency.
- Photon momentum increases with frequency and decreases with wavelength. The wave's intensity determines photon number, not the momentum of each photon.

Step 1: Compare the wavelengths X-rays have much shorter wavelengths than microwaves, TV waves and AM radio waves. Equivalently, they have the greatest frequency among the four listed types of radiation.

Step 2: Apply the photon momentum relation Since h and c are constants, the radiation with the greatest frequency has the greatest momentum per photon. All three other choices have longer wavelengths, so their photons have smaller momentum. Equal propagation speed in vacuum does not imply equal photon momentum.

Step 3: Conclusion X-ray photons have the largest momentum among the given waves. Hence, the correct option is (A).

Quick Tip to Solve: For a largest-photon-momentum question, select the shortest wavelength in the listed spectrum.

9. The kinetic energy of an alpha particle is four times the kinetic energy of a proton. The ratio $\frac{\lambda_\alpha}{\lambda_p}$ of de Broglie wavelengths associated with them will be:

[1 mark]

- (A) $\frac{1}{16}$
- (B) $\frac{1}{8}$
- (C) $\frac{1}{4}$
- (D) $\frac{1}{2}$

Correct Answer: (C) $\frac{1}{4}$

Solution:

Concept:

- For non-relativistic motion, the de Broglie wavelength is $\lambda = h/p = h/\sqrt{2mK}$, where m is particle mass and K is kinetic energy.
- An alpha particle has approximately four times the mass of a proton: $m_\alpha = 4m_p$. Here the given energies satisfy $K_\alpha = 4K_p$.

Step 1: Form the wavelength ratio Because wavelength is inversely proportional to the square root of the product of mass and kinetic energy, both changes must be included:

$$\frac{\lambda_{\alpha}}{\lambda_p} = \sqrt{\frac{m_p K_p}{m_{\alpha} K_{\alpha}}}.$$

Step 2: Substitute both factors of four The mass-energy product for the alpha particle is sixteen times that for the proton, giving

$$\frac{\lambda_{\alpha}}{\lambda_p} = \sqrt{\frac{1}{4 \times 4}} = \frac{1}{4}.$$

Option (A) omits the square root, while option (D) accounts for only one factor of four. Option (B) also fails the square-root relation.

Step 3: Conclusion The ratio is $\lambda_{\alpha}/\lambda_p = 1/4$. Hence, the correct option is (C).

Quick Tip to Solve: Multiply the mass ratio by the kinetic-energy ratio before taking the inverse square root.

10. A glass slab ($\mu = 1.5$) of thickness 6 cm is placed over a paper. The shift in the letters printed on the paper will be: [1 mark]

- (A) 2 cm
- (B) 1 cm
- (C) 4 cm
- (D) 3 cm

Correct Answer: (A) 2 cm

Solution:

Concept:

- When viewed nearly normally from air, an object at real depth t in glass appears at depth t/μ , where μ is the refractive index of glass relative to air.
- The apparent upward shift is the difference between real and apparent depth: $s = t(1 - 1/\mu)$.

Step 1: Find the apparent depth The letters lie under the slab, at a real depth of 6 cm measured from its top surface. Refraction at the glass-air interface makes them appear closer to that surface:

$$t_{\text{apparent}} = \frac{6}{1.5} = 4 \text{ cm}.$$

Step 2: Calculate the displacement The shift is the decrease in apparent depth, not the apparent depth itself:

$$s = 6 - 4 = 2 \text{ cm}.$$

Thus 4 cm, option (C), confuses apparent depth with shift. Neither 1 cm nor 3 cm follows from the given refractive index.

Step 3: Conclusion The letters appear shifted upward by 2 cm. Hence, the correct option is (A).

Quick Tip to Solve: Compute apparent depth first, then subtract it from slab thickness to obtain the upward shift.

11. The dimensions of $(\mu\epsilon)^{-1}$, where ϵ is permittivity and μ is permeability of a medium, are: [1 mark]

- (A) $[M^0 L^1 T^{-1}]$
- (B) $[M^0 L^2 T^{-2}]$
- (C) $[M^1 L^2 T^{-2}]$
- (D) $[M^1 L^{-1} T^1]$

Correct Answer: (B) $[M^0 L^2 T^{-2}]$

Solution:

Concept:

- The electromagnetic wave speed in a medium is $v = 1/\sqrt{\mu\epsilon}$, where μ is its permeability and ϵ its permittivity.
- Speed has dimensions $[LT^{-1}]$. Therefore a squared speed has dimensions $[L^2 T^{-2}]$, independent of mass.

Step 1: Identify the requested quantity The printed expression is the inverse of the product, $(\mu\epsilon)^{-1}$. Squaring the wave-speed relation gives

$$(\mu\epsilon)^{-1} = v^2.$$

Taking the dimensions of the product itself would reverse the required powers of length and time.

Step 2: Square the dimensions of speed Hence the dimensional formula is

$$[(\mu\epsilon)^{-1}] = [LT^{-1}]^2 = [M^0 L^2 T^{-2}].$$

Option (A) represents speed, not speed squared. Option (C) includes an unwanted mass factor, and option (D) has incorrect powers of mass, length and time.

Step 3: Conclusion The required dimensions are $[M^0 L^2 T^{-2}]$. Hence, the correct option is (B).

Quick Tip to Solve: Replace the inverse product of permeability and permittivity by wave speed squared before checking dimensions.

12. A charged particle gains a speed of 10^6 ms^{-1} , when accelerated from rest through a potential difference 10 kV. It enters a region of magnetic field of 0.4 T such that $\vec{v} \perp \vec{B}$. The radius of circular path described by it is: [1 mark]

- (A) 2.5 cm
- (B) 5 cm
- (C) 8 cm
- (D) 10 cm

Correct Answer: (B) 5 cm

Solution:

Concept:

- Acceleration from rest through a potential difference of magnitude V gives kinetic energy $|q|V = mv^2/2$, where m and q are the particle's mass and charge.
- For velocity perpendicular to a uniform magnetic field, the magnetic force provides centripetal force: $|q|vB = mv^2/r$, hence $r = mv/(|q|B)$.

Step 1: Eliminate the unknown mass and charge The energy equation gives $m/|q| = 2V/v^2$. Substituting this into the radius formula yields

$$r = \frac{m}{|q|} \frac{v}{B} = \frac{2V}{vB}.$$

Thus the given accelerating voltage and speed suffice; the identity of the particle is unnecessary.

Step 2: Convert the voltage and calculate Use $V = 10 \text{ kV} = 10^4 \text{ V}$, $v = 10^6 \text{ m s}^{-1}$ and $B = 0.4 \text{ T}$:

$$r = \frac{2 \times 10^4}{10^6 \times 0.4} = 0.05 \text{ m} = 5 \text{ cm}.$$

The 2.5 cm choice omits the factor of two in the energy relation. The 8 cm and 10 cm choices do not satisfy both the energy and force equations.

Step 3: Conclusion The circular path has radius 5 cm. Hence, the correct option is (B).

Quick Tip to Solve: When accelerating voltage and final speed are given, use $r = 2V/(vB)$ to avoid finding the charge-to-mass ratio separately.

13. Assertion (A): In Rutherford's alpha particle scattering experiment, the presence of only few alpha particles at angle of scattering π led him to the discovery of nucleus.

Reason (R): The size of nucleus is approximately 10^{-5} times the size of an atom and therefore only few alpha particles are rebounded. [1 mark]

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

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

Solution:

Concept:

- Rutherford scattering is caused by electrostatic repulsion between the positively charged alpha particle and the concentrated positive nuclear charge.
- A scattering angle of $\pi \text{ rad} = 180^\circ$ corresponds to backward scattering in a nearly head-on encounter. Nuclear dimensions are of order 10^{-15} m , compared with atomic dimensions of order 10^{-10} m .

Step 1: Evaluate the assertion The rare alpha particles scattered directly backward revealed a very small, massive, positively charged central region capable of strongly repelling them. This observation was crucial evidence for the nucleus, so the assertion is true.

Step 2: Evaluate the reason The approximate ratio of nuclear to atomic size is $10^{-15}/10^{-10} = 10^{-5}$, as printed. The nucleus occupies a minute region of the atom, so only a few incident alpha particles pass sufficiently close to it for almost head-on scattering. Thus the reason is true.

Step 3: Check the explanatory connection The tiny extent of the concentrated positive charge explains why strong backward deflections are so rare. Most alpha particles pass far from the nucleus and undergo little deflection. The reason therefore explains the rarity highlighted in the assertion; options (B), (C) and (D) incorrectly deny this link or the truth of a statement.

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

Quick Tip to Solve: Link rare backward scattering to the tiny nucleus; link the large deflection itself to its concentrated positive charge.

14. Assertion (A): The Balmer series in hydrogen atom spectrum is formed when the electron jumps from higher energy state to the ground state.

Reason (R): In Bohr's model of hydrogen atom, the electron can jump between successive orbits only. [1 mark]

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

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

Solution:

Concept:

- A hydrogen spectral series is identified by the final principal quantum number: Balmer transitions end at $n = 2$, while Lyman transitions end at the ground state $n = 1$.
- In Bohr's model, a transition between stationary energy levels emits or absorbs a photon with energy $h\nu = |E_i - E_f|$. The initial and final orbits need not be successive.

Step 1: Evaluate the assertion Balmer lines arise when an electron falls from $n = 3, 4, 5, \dots$ to $n = 2$, the first excited state. A fall to the ground state $n = 1$ belongs to the Lyman series. Therefore the assertion is false.

Step 2: Evaluate the reason Bohr's model does not restrict transitions to neighbouring orbits. For example, the transition $n = 4 \rightarrow n = 2$ skips an orbit and produces a Balmer line. The claim that jumps occur only between successive orbits is therefore false.

Step 3: Apply the assertion-reason code Since both statements are false, no explanatory relationship is valid. Options (A) and (B) wrongly treat both as true, and option (C) wrongly treats the assertion as true. The printed code for two false statements is (D).

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

Quick Tip to Solve: Identify a hydrogen series by its final orbit: $n = 1$ means Lyman and $n = 2$ means Balmer, even when intermediate orbits are skipped.

15. Assertion (A): During formation of a nucleus, the mass defect produced is the source of the binding energy of the nucleus.

Reason (R): For all nuclei, the value of binding energy per nucleon increases with mass number.

[1 mark]

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

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

Solution:

Concept:

- The mass defect is $\Delta m = Zm_p + (A - Z)m_n - M$, where M is the nuclear mass, Z is the proton number and A is the mass number.
- Binding energy is $B = \Delta mc^2$; binding energy per nucleon is B/A , which measures the average binding of a nucleon.

Step 1: Evaluate the assertion When free nucleons bind into a nucleus, energy is released and the nucleus has less mass than the sum of the separate nucleon masses. This mass difference corresponds to the binding energy through $B = \Delta mc^2$. The assertion is true.

Step 2: Evaluate the reason Binding energy per nucleon generally rises for light nuclei, reaches a broad maximum near the iron-nickel region, and then slowly decreases for heavy nuclei. It does not increase with mass number for all nuclei, so the reason is false.

Step 3: Test the explanatory link A false statement cannot explain the true assertion. The assertion follows from mass-energy equivalence, not from a universal increase of B/A . Options (A) and (B) wrongly call the reason true; option (D) wrongly calls the assertion false.

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

Quick Tip to Solve: For claims about all nuclei, recall the peak of the binding-energy-per-nucleon curve near iron before judging the trend.

16. Assertion (A): The impurities in p-type Si are not pentavalent atoms.

Reason (R): The hole density in valance band in p-type semiconductor is almost equal to the acceptor density. [1 mark]

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

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

Solution:

Concept:

- Trivalent impurities are acceptors in silicon and produce p-type material; pentavalent impurities are donors and produce n-type material.
- In an ordinary, uncompensated p-type semiconductor with ionised acceptors, charge neutrality gives $p = n + N_A$. Here p , n and N_A denote hole, electron and acceptor number densities.

Step 1: Evaluate the assertion Silicon has four valence electrons. A trivalent impurity leaves one bond short of an electron and can accept an electron, creating a mobile hole. A pentavalent impurity instead supplies an extra electron. Thus the dopants used to make p-type silicon are not pentavalent, and the assertion is true.

Step 2: Evaluate the reason Each ionised acceptor produces approximately one hole. Since holes are the majority carriers, $p \gg n$; hence charge neutrality gives $p \simeq N_A$. Under the usual extrinsic-semiconductor conditions assumed here, the reason is true.

Step 3: Test whether the reason explains the assertion The reason states a carrier-density relation after acceptor doping. It does not explain why a pentavalent dopant donates an electron instead of producing a hole; that distinction follows from valence and bonding. Thus it does not correctly explain the assertion. Option (A) assigns an explanatory link that is absent, while (C) and (D) incorrectly reject a true statement.

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: Judge the truth of both statements first; a correct carrier-density formula need not explain the required dopant valency.

Section B (10 marks)

17(a). A point object is placed in air at a distance $R/3$ in front of a convex surface of radius of curvature R , separating air from a medium of refractive index n (< 4). Find the nature and position of the image formed. [2 marks]

Solution:

Concept:

- For paraxial refraction at a spherical surface, $n_2/v - n_1/u = (n_2 - n_1)/R_s$, where u and v are object and image distances measured from the pole, and R_s is the signed radius of curvature.
- With the Cartesian sign convention, distances measured along the incident light are positive. A negative image distance means a virtual image on the incident side of the surface.

Step 1: Assign signs to the given distances Take light to travel from the object in air towards the refracting medium. The object is before the pole, whereas the centre of curvature of the convex surface lies inside the medium. Therefore

$$n_1 = 1, \quad n_2 = n, \quad u = -\frac{R}{3}, \quad R_s = +R.$$

Here R denotes the positive magnitude supplied in the question.

Step 2: Apply the refraction formula Substituting the signed quantities gives

$$\begin{aligned} \frac{n}{v} - \frac{1}{-R/3} &= \frac{n-1}{R}, \\ \frac{n}{v} + \frac{3}{R} &= \frac{n-1}{R}, \\ \frac{n}{v} &= \frac{n-4}{R}, \\ v &= \frac{nR}{n-4} = -\frac{nR}{4-n}. \end{aligned}$$

Since $n < 4$, the denominator in the first expression for v is negative. The emerging rays therefore appear to originate from the air side when extended backwards.

Step 3: Conclusion The image is virtual and lies in air, in front of the convex surface, at a distance $\frac{nR}{4-n}$ from its pole; its signed position is $v = -\frac{nR}{4-n}$.

Quick Tip to Solve: Keep $u = -R/3$ and the convex surface radius positive; then the given condition $n < 4$ immediately fixes the image as virtual.

17(b). In Young's double slit experimental set-up, the intensity of the central maximum is I_0 . Calculate the intensity at a point where the path difference between two interfering waves is $\lambda/3$. [2 marks]

Solution:

Concept:

- In the usual Young's double-slit arrangement, the two coherent waves have equal individual intensities I_s , giving $I = 4I_s \cos^2(\phi/2)$.
- A path difference Δ corresponds to phase difference $\phi = 2\pi\Delta/\lambda$, where λ is the wavelength. At the central maximum, $\Delta = 0$ and $I_0 = 4I_s$.

Step 1: Convert the path difference to a phase difference A full wavelength of path difference produces a phase difference of 2π . For the given path difference, therefore,

$$\phi = \frac{2\pi}{\lambda} \frac{\lambda}{3} = \frac{2\pi}{3}.$$

The two waves are neither exactly in phase nor exactly opposite in phase, so the intensity is intermediate between a maximum and zero.

Step 2: Express the intensity in terms of the central maximum Replace $4I_s$ by the given central-maximum intensity I_0 . The interference factor contains half the phase difference:

$$\begin{aligned} I &= I_0 \cos^2\left(\frac{\phi}{2}\right) \\ &= I_0 \cos^2\left(\frac{\pi}{3}\right) \\ &= I_0 \left(\frac{1}{2}\right)^2 = \frac{I_0}{4}. \end{aligned}$$

This ratio refers to intensity, which is proportional to the square of the resultant amplitude.

Step 3: Conclusion The intensity at path difference $\lambda/3$ is $I = I_0/4$, one quarter of the central-maximum intensity.

Quick Tip to Solve: Use $I/I_0 = \cos^2(\pi\Delta/\lambda)$; inserting $\Delta = \lambda/3$ directly gives $\cos^2(\pi/3) = 1/4$.

18. A wire of resistance X ohm is gradually stretched till its length becomes twice its original length. If its new resistance becomes 40Ω , find the value of X . [2 marks]

Solution:

Concept:

- A uniform wire has resistance $\mathcal{R} = \rho L/A$, where ρ is its resistivity, L its length and A its cross-sectional area.
- For uniform stretching without loss of material, the wire's volume is constant: $AL = A'L'$. Assume its resistivity stays constant, as usual for this question.

Step 1: Find the new cross-sectional area Denote the original length and area by L and A . Stretching

changes both dimensions. Since the final length is $L' = 2L$, conservation of volume gives

$$A'L' = AL \Rightarrow A'(2L) = AL \Rightarrow A' = \frac{A}{2}.$$

The wire therefore becomes thinner as it becomes longer; keeping its original area would give an incorrect resistance ratio.

Step 2: Compare the resistances and substitute the final value With the same resistivity before and after stretching,

$$\begin{aligned}\frac{\mathcal{R}'}{\mathcal{R}} &= \frac{L'}{L} \frac{A}{A'} = 2 \times 2 = 4, \\ \mathcal{R}' &= 4\mathcal{R}, \\ 40\ \Omega &= 4(X\ \Omega), \\ X &= \frac{40}{4} = 10.\end{aligned}$$

One factor of two comes from the increased length and the other from the reduced area.

Step 3: Conclusion The original resistance is $10\ \Omega$, so $X = 10$.

Quick Tip to Solve: For a stretched wire of unchanged volume and resistivity, resistance scales as length squared; doubling the length multiplies resistance by four.

19. A circular coil of wire having 200 turns, each of radius 4.0 cm is placed in a horizontal plane. It carries a current of 0.40 A in clockwise direction. Find the magnitude and direction of the magnetic field at the centre of the coil. [2 marks]

Solution:

Concept:

- The magnetic field at the centre of a circular coil is $B = \frac{\mu_0 N I}{2r}$, where N is the number of turns, I the current and r the radius of each turn.
- The right-hand thumb rule gives the field direction: curl the fingers along the current and the thumb points along the field normal to the coil's plane.

Step 1: Convert the radius and substitute the data All turns carry the same current and their fields at the centre add. Use $N = 200$, $I = 0.40\ \text{A}$, $r = 4.0\ \text{cm} = 4.0 \times 10^{-2}\ \text{m}$ and $\mu_0 = 4\pi \times 10^{-7}\ \text{T m A}^{-1}$.

$$\begin{aligned}B &= \frac{(4\pi \times 10^{-7})(200)(0.40)}{2(4.0 \times 10^{-2})} \\ &= 4\pi \times 10^{-4}\ \text{T} = 1.26 \times 10^{-3}\ \text{T}.\end{aligned}$$

Step 2: Apply the right-hand rule Viewed from above the horizontal coil, the current is clockwise. Curling the fingers of the right hand clockwise makes the thumb point away from the observer, vertically downwards. The field therefore enters the horizontal plane of the coil.

Step 3: Conclusion The magnetic field at the centre is $B = 1.26 \times 10^{-3}\ \text{T}$, directed vertically downwards for clockwise current viewed from above.

Quick Tip to Solve: Convert the radius to metres and multiply the single-loop field by 200; clockwise as viewed from above means a downward field.

20. (a) Why is the mass of a nucleus always less than the sum of the masses of its constituents, i.e. free neutrons and free protons?

(b) How is Coulomb repulsion between protons in a nucleus overcome? Explain.

[2 marks]

Solution:

Concept:

- The mass defect of a nucleus containing Z protons and $A - Z$ neutrons is $\Delta m = Zm_p + (A - Z)m_n - M$, where M is the nuclear mass and m_p, m_n are the free nucleon masses.
- The binding energy is $E_b = \Delta mc^2$. Nuclear attraction acts between nucleons over very short distances, of the order of a few femtometres.

Step 1: Explain the smaller nuclear mass in part (a) When initially free protons and neutrons combine to form a bound nucleus, energy is released. The bound system consequently has less total energy than the separated nucleons. By mass-energy equivalence, this energy decrease corresponds to a decrease in rest mass:

$$M = Zm_p + (A - Z)m_n - \frac{E_b}{c^2}.$$

Thus, the positive binding energy accounts for the mass defect. The same energy must be supplied to separate the nucleus completely into free nucleons.

Step 2: Explain how protons remain bound in part (b) Protons repel one another electrically, but the attractive strong nuclear force between nearby nucleons is much stronger than Coulomb repulsion at typical nuclear separations. It acts between proton-proton, neutron-neutron and proton-neutron pairs and is approximately charge independent. Neutrons therefore contribute nuclear attraction without adding Coulomb repulsion, helping to bind the nucleus.

Step 3: Conclusion (a) The missing mass is the mass equivalent E_b/c^2 of the released binding energy. (b) At nuclear distances, strong nuclear attraction overcomes the Coulomb repulsion and binds the nucleons.

Quick Tip to Solve: Link the smaller mass to released binding energy, and distinguish the short-range nuclear attraction from proton-proton electrical repulsion.

21. The threshold frequency for a given metal is 3.6×10^{14} Hz. If monochromatic radiations of frequency 6.8×10^{14} Hz are incident on this metal, find the cut-off potential for the photoelectrons.

[2 marks]

Solution:

Concept:

- Einstein's photoelectric equation is $K_{\max} = h\nu - \phi = h(\nu - \nu_0)$, where ν is the incident frequency, ν_0 the threshold frequency and $\phi = h\nu_0$ the work function.
- The cut-off or stopping potential magnitude V_0 satisfies $eV_0 = K_{\max}$, since the retarding field must stop even the fastest photoelectrons.

Step 1: Find the energy available as kinetic energy The incident frequency exceeds the threshold, so emission occurs. Only the photon energy above the work function becomes maximum kinetic energy.

The frequency difference is

$$\nu - \nu_0 = (6.8 - 3.6) \times 10^{14} = 3.2 \times 10^{14} \text{ Hz.}$$

Taking $h = 6.63 \times 10^{-34} \text{ J s}$,

$$K_{\max} = (6.63 \times 10^{-34})(3.2 \times 10^{14}) = 2.1216 \times 10^{-19} \text{ J.}$$

Step 2: Calculate the stopping potential Divide the maximum kinetic energy by the magnitude of the electron charge, $e = 1.6 \times 10^{-19} \text{ C}$:

$$V_0 = \frac{K_{\max}}{e} = \frac{2.1216 \times 10^{-19}}{1.6 \times 10^{-19}} = 1.326 \text{ V.}$$

This is a retarding potential: the collector must be negative relative to the emitting metal to oppose the emitted electrons.

Step 3: Conclusion The cut-off potential has magnitude $V_0 \approx 1.33 \text{ V}$; the collector is approximately 1.33 V negative relative to the emitter.

Quick Tip to Solve: Subtract the threshold frequency before using $V_0 = (h/e)(\nu - \nu_0)$; the full photon energy is not available to stop the electron.

Section C (21 marks)

22(a). Two small solid metal balls A and B of radii R and $2R$ having charge densities 2σ and 3σ respectively are kept far apart. Find the charge densities on A and B after they are connected by a conducting wire. [3 marks]

Solution:

Concept:

- Excess charge on a metal sphere resides on its surface. The charge is $Q = 4\pi r^2 \sigma_s$, where r is the radius and σ_s is the surface charge density.
- When two spheres are connected by a conducting wire, charge flows until their potentials are equal. For spheres far apart, $V = kQ/r$, where $k = 1/(4\pi\epsilon_0)$.
- The total charge of the isolated pair is conserved; the thin connecting wire is taken to carry negligible charge.

Step 1: Calculate the initial total charge The radii are R and $2R$, and the initial surface densities are 2σ and 3σ . Therefore,

$$\begin{aligned}Q_A &= 4\pi R^2(2\sigma) = 8\pi R^2\sigma, \\Q_B &= 4\pi(2R)^2(3\sigma) = 48\pi R^2\sigma, \\Q_{\text{total}} &= 56\pi R^2\sigma.\end{aligned}$$

The second sphere has four times the surface area of the first; its initial charge must include this area factor.

Step 2: Equate the final potentials Let Q'_A and Q'_B be the final charges. Because the spheres are far

apart, their mutual effects on surface potentials are negligible. At equilibrium,

$$\frac{kQ'_A}{R} = \frac{kQ'_B}{2R} \Rightarrow Q'_B = 2Q'_A.$$

Combining this with charge conservation gives

$$3Q'_A = 56\pi R^2\sigma,$$

$$Q'_A = \frac{56}{3}\pi R^2\sigma, \quad Q'_B = \frac{112}{3}\pi R^2\sigma.$$

Step 3: Divide each final charge by its surface area The radii remain unchanged. The final charge densities are therefore

$$\sigma'_A = \frac{Q'_A}{4\pi R^2} = \frac{14}{3}\sigma,$$

$$\sigma'_B = \frac{Q'_B}{4\pi(2R)^2} = \frac{7}{3}\sigma.$$

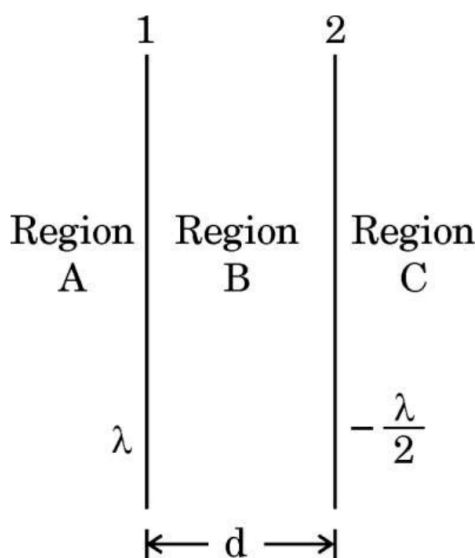
Thus equal potentials give charge proportional to radius, while surface charge density is inversely proportional to radius. The smaller sphere has twice the final surface density of the larger one.

Step 4: Conclusion After connection, the surface charge densities are $\sigma'_A = \frac{14\sigma}{3}$ and $\sigma'_B = \frac{7\sigma}{3}$.

Quick Tip to Solve: Conserve total charge and equate Q/R , not charge densities; for connected distant spheres, $\sigma_s r$ is the same on both.

OR

22(b). Two infinitely long straight wires '1' and '2' are placed d distance apart, parallel to each other, as shown in the figure. They are uniformly charged having charge densities λ and $-\frac{\lambda}{2}$ respectively. Locate the position of the point from wire '1' at which the net electric field is zero and identify the region in which it lies. [3 marks]



Solution:**Concept:**

- The electric field magnitude at perpendicular distance r from an infinite wire of linear charge density λ is $E = |\lambda|/(2\pi\epsilon_0 r)$, where ϵ_0 is the permittivity of free space.
- The field points away from a positive wire and towards a negative wire. A zero resultant requires equal magnitudes in opposite directions, so directions must be checked before equating magnitudes.

Step 1: Exclude the region between the wires Take wire 1 at $x = 0$ and wire 2 at $x = d$, with $\lambda > 0$. In region B, the field of wire 1 points right, away from its positive charge. The field of wire 2 also points right, towards its negative charge. Thus the fields add throughout region B and cannot cancel. Reversing both charge signs reverses both fields and does not change the position of cancellation.

Step 2: Check the outer region on the side of wire 1 In region A, let the distance from wire 1 be $s > 0$. The distance from wire 2 is $s + d$. Although the fields oppose, their magnitude ratio is

$$\frac{E_1}{E_2} = \frac{|\lambda|/s}{|\lambda|/[2(s+d)]} = \frac{2(s+d)}{s} > 2.$$

The nearer wire also has the larger charge density, so its field always dominates. There is no finite zero-field point in region A.

Step 3: Equate the opposing fields in region C Let the required point be at perpendicular distance $x > d$ from wire 1. Its distance from wire 2 is $x - d$. Here the positive wire produces a rightward field and the negative wire produces a leftward field. Equating their magnitudes gives

$$\frac{|\lambda|}{2\pi\epsilon_0 x} = \frac{|\lambda|/2}{2\pi\epsilon_0(x-d)}, \quad 2(x-d) = x.$$

This equation has a solution satisfying the assumed condition $x > d$, so the cancellation is physically in this region.

Step 4: Conclusion The net field vanishes at $x = 2d$ from wire 1, in region C, beyond wire 2. Equivalently, it is at distance d from wire 2 on the side away from wire 1.

Quick Tip to Solve: For unequal opposite line charges, look outside on the weaker-charge side; use the line-charge law $E \propto 1/r$, not the point-charge inverse-square law.

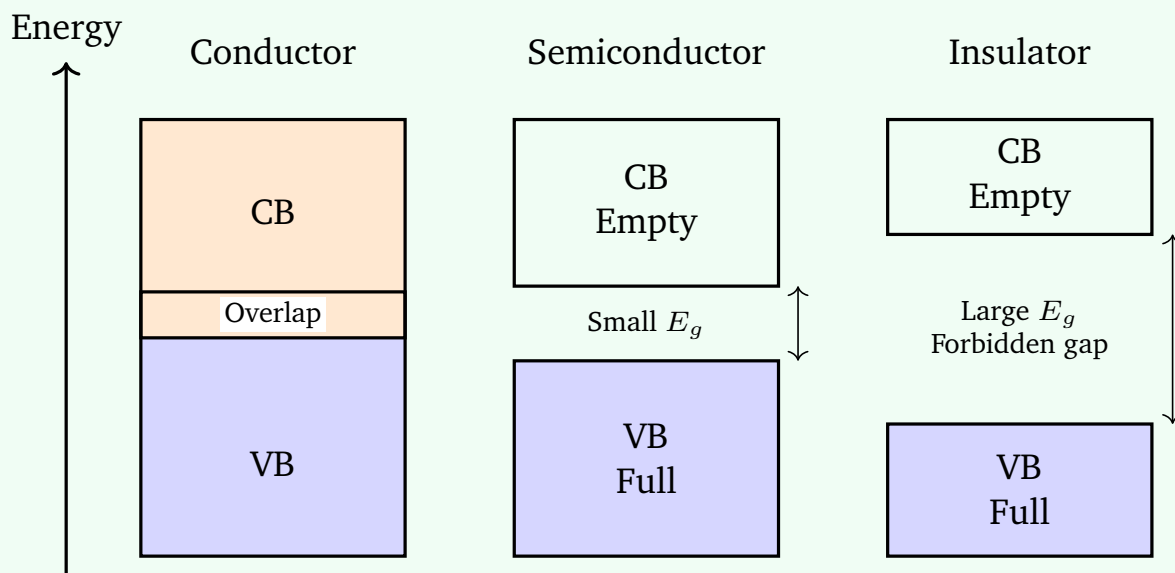
23. (a) Draw the energy-band diagrams for conductors, semiconductors and insulators at $T = 0$ K. How is an electron-hole pair formed in a semiconductor at room temperature?

(b) Carbon and silicon both, are members of IV group of periodic table and have the same lattice structure. Carbon is an insulator whereas silicon is a semiconductor. Explain. [3 marks]

Solution:**Concept:**

- The valence band contains the valence-electron states; the conduction band contains higher-energy states that permit mobile electrons. The forbidden energy gap is $E_g = E_C - E_V$, the difference between the conduction-band minimum and the valence-band maximum.
- Electrical conduction requires accessible unoccupied states. An electron thermally promoted from a full valence band to the conduction band leaves a hole; both the electron and the hole can carry current.

Step 1: Draw and compare the bands at absolute zero (a) A conductor has a partially filled band or overlapping valence and conduction bands, so nearby vacant states are available even at $T = 0\text{ K}$. The diagram shows the overlapping-band case. In an intrinsic semiconductor at 0 K , the valence band is full and the conduction band is empty, separated by a small forbidden gap. In an insulator the valence band is likewise full and conduction band empty, but the gap is much larger. Thus an ideal intrinsic semiconductor has no thermally generated charge carriers at absolute zero.



Energy bands at $T = 0\text{ K}$. VB: valence band; CB: conduction band. The conductor sketch shows band overlap.

Step 2: Explain thermal generation of an electron-hole pair At room temperature some valence electrons acquire enough thermal energy to cross the semiconductor's gap into the conduction band. The missing electron leaves a positively behaving vacancy, called a hole, in the valence band. Each such excitation creates one conduction electron and one hole together. In the covalent-bond picture this is the breaking of a bond by thermal excitation; the promoted electron is free to move through the crystal.

Step 3: Compare carbon and silicon band gaps (b) Equal valency and the same lattice structure do not imply equal energy gaps, because the bonding and electronic energy levels differ. Carbon in the diamond structure has strong covalent bonds and a wide gap of about 5.4 eV . Ordinary thermal energy cannot produce an appreciable carrier population across this gap, so diamond is an insulator. Silicon has a much smaller gap of about 1.1 eV , allowing a useful population of electron-hole pairs at room temperature and hence semiconductor behaviour. The carbon comparison here refers to diamond, as indicated by the stated lattice structure.

Step 4: Conclusion Conductors have a partially filled band or overlapping bands; semiconductors have a small gap and insulators a large gap. Thermal excitation across silicon's small gap creates electron-hole pairs, whereas the wide gap of diamond makes carbon insulating under ordinary conditions.

Quick Tip to Solve: In the zero-temperature sketches, label the semiconductor and insulator valence bands full and conduction bands empty; distinguish them by the gap width, not by valency.

24. A capacitor of plate area A and plate separation d is charged by a battery to voltage V . The battery is disconnected and plates are slowly pulled apart till the separation becomes $2d$. Find the value of:
- potential difference between the plates,
 - electric field between the plates,
 - work done in pulling the plates apart.

[3 marks]

Solution:

Concept:

- For a parallel-plate capacitor in air or vacuum, neglecting edge effects, $C = \epsilon_0 A/s$, where A is the plate area and s their separation.
- Disconnecting the battery leaves the charge Q on each isolated plate unchanged. The voltage is Q/C , the uniform field is $E = Q/(\epsilon_0 A)$, and the stored energy is $U = Q^2/(2C)$.
- When the plates are separated slowly, their kinetic energy does not change appreciably. The positive external work against attraction equals the increase in electrostatic energy.

Step 1: Establish the conserved charge and final capacitance Initially the separation is d , so the capacitance and the charge supplied by the battery are

$$C_i = \frac{\epsilon_0 A}{d}, \quad Q = C_i V = \frac{\epsilon_0 A V}{d}.$$

After disconnection no charge flows to or from the plates. Increasing the separation to $2d$ gives

$$C_f = \frac{\epsilon_0 A}{2d} = \frac{C_i}{2}.$$

Thus charge, rather than voltage, is the fixed quantity during the displacement.

Step 2: Calculate the new voltage and electric field (a) Using the same charge with the reduced capacitance,

$$V_f = \frac{Q}{C_f} = \frac{C_i V}{C_i/2} = 2V.$$

(b) The electric field between parallel plates is the potential difference divided by their separation. Therefore

$$E_f = \frac{V_f}{2d} = \frac{2V}{2d} = \frac{V}{d}.$$

It remains equal to the initial field because the fixed surface charge density Q/A sets the field. Its direction is from the positive plate to the negative plate.

Step 3: Find the increase in stored energy (c) The initial and final energies are

$$U_i = \frac{1}{2} C_i V^2 = \frac{\epsilon_0 A V^2}{2d}, \quad U_f = \frac{Q^2}{2C_f} = 2U_i.$$

There is no battery energy exchange during separation. The applied force must oppose the attractive

force of the plates, so the work supplied by the external agent is positive:

$$W_{\text{ext}} = U_f - U_i = U_i = \frac{\epsilon_0 AV^2}{2d}.$$

Step 4: Conclusion $V_f = 2V$, $E_f = V/d$ (unchanged), and $W_{\text{ext}} = \epsilon_0 AV^2/(2d)$. These expressions give voltage in volts, field in volts per metre, and work in joules when SI inputs are used.

Quick Tip to Solve: Underline “battery disconnected”: keep Q fixed. Doubling the separation halves C , doubles the voltage and energy, and leaves the field unchanged.

25. Using the Huygens’ principle, briefly describe reflection of a plane wavefront from a reflecting surface. Hence, prove the laws of reflection. [3 marks]

Solution:

Concept:

- Huygens’ principle states that every point on a wavefront acts as a source of secondary wavelets; their forward envelope gives the subsequent wavefront.
- A light ray is normal to its wavefront. In reflection the incident and reflected waves travel in the same medium with the same speed v .

Step 1: Construct the reflected wavefront Let a plane wavefront AB strike a plane reflecting surface obliquely, with end A reaching it first. In time t , the other end B travels along its incident ray to a point C on the surface. Thus $BC = vt$. Meanwhile the secondary reflected wavelet from A grows to radius $AD = vt$. Draw from C the tangent CD to this wavelet, meeting it at D . This tangent is the reflected plane wavefront: it is also the common envelope of the wavelets emitted by intervening points of the surface as the incident front reaches them.

Step 2: Prove equality of the angles Since BC is normal to the incident wavefront AB , triangle ABC is right-angled at B . The tangent CD is perpendicular to the radius AD , so triangle ADC is right-angled at D . Both triangles have the same hypotenuse AC , and $BC = AD = vt$. Therefore they are congruent. Equivalently, if i and r are the angles of incidence and reflection measured from the surface normal,

$$\sin i = \frac{BC}{AC} = \frac{vt}{AC}, \quad \sin r = \frac{AD}{AC} = \frac{vt}{AC}.$$

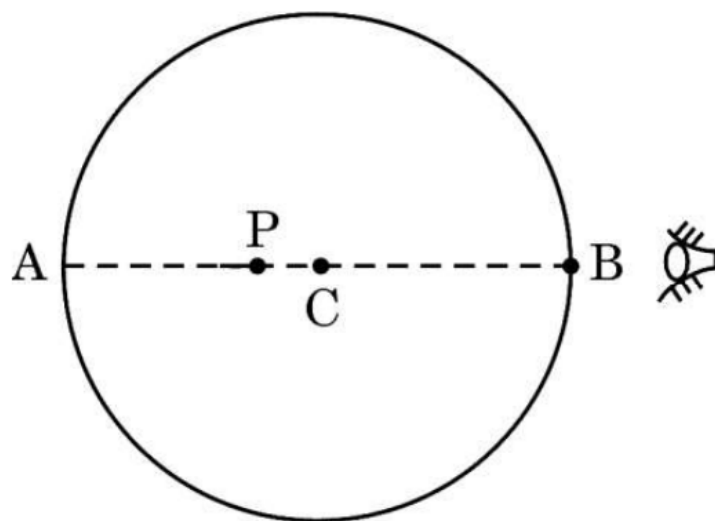
Here the angle between the incident wavefront and surface equals i , and that between the reflected wavefront and surface equals r , because the corresponding rays and normals are perpendicular to these lines. Hence $\sin i = \sin r$, giving $i = r$.

Step 3: Establish the common plane Take the construction in the plane containing the incident ray and the normal to the reflecting surface. The reflected wavelet radius AD , which is normal to CD and represents the reflected ray, lies in this same plane. Thus the incident ray, reflected ray and surface normal are coplanar.

Step 4: Conclusion Huygens' construction yields both laws of reflection: $i = r$, and the incident ray, reflected ray and normal at the point of incidence lie in the same plane.

Quick Tip to Solve: Use equal distances $BC = AD = vt$ and the shared hypotenuse AC ; angles between wavefronts and the surface equal the corresponding ray angles with the normal.

26. An air bubble is trapped at point P ($CP = 1.75$ cm) in a spherical glass ball ($n = 1.5$) of radius 7 cm as shown in the figure. Find the nature and position of the image when viewed from side B . Show the image formation by drawing a ray diagram. [3 marks]



Solution:

Concept:

- For paraxial refraction at a spherical surface, $\frac{n_2}{v} - \frac{n_1}{u} = \frac{n_2 - n_1}{R}$, where n_1, n_2 are incident and emergent refractive indices and u, v, R are signed distances from the surface pole.
- Use the Cartesian sign convention: distances along the incident light are positive. A negative image distance for this real object indicates a virtual image on the incident side of the surface.

Step 1: Identify the refracting surface and signed distances The observer is to the right of B , so light from the bubble at P travels through glass and emerges into air at the right spherical surface. Treat the small bubble as a point object inside glass. In the printed figure, P is to the left of the centre C , hence its distance from B is

$$BP = BC + CP = 7 + 1.75 = 8.75 \text{ cm.}$$

Taking B as origin and rightward distances as positive gives

$$n_1 = 1.5, \quad n_2 = 1, \quad u = -8.75 \text{ cm}, \quad R = -7 \text{ cm.}$$

The radius is negative because the centre of curvature C lies to the left of B .

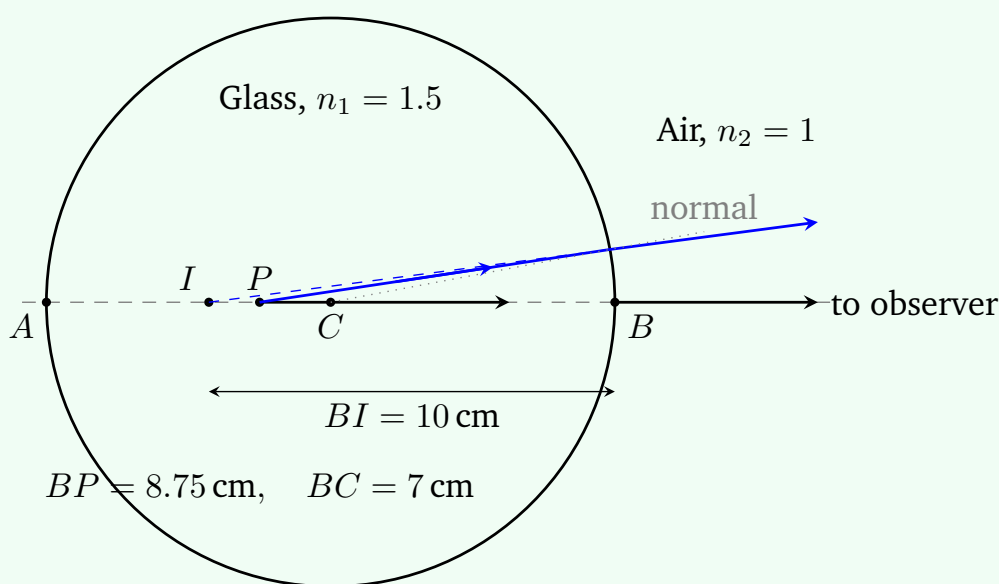
Step 2: Substitute in the spherical refraction formula Substituting the signed quantities, with all

distances in centimetres,

$$\begin{aligned}\frac{1}{v} - \frac{1.5}{-8.75} &= \frac{1 - 1.5}{-7}, \\ \frac{1}{v} + \frac{6}{35} &= \frac{1}{14}, \\ \frac{1}{v} &= \frac{1}{14} - \frac{6}{35} = -\frac{1}{10} \text{ cm}^{-1}.\end{aligned}$$

The sign places the image inside the ball on the left of the exit surface. It lies farther from B than the actual bubble does.

Step 3: Trace the emergent rays A ray along PCB emerges undeviated because it meets the surface normally. A nearby oblique ray bends away from its local normal, the radius through the point of incidence, on emerging from glass to air. The emerging rays diverge; their backward extensions meet the axis at I , to the left of P . The diagram shows the paraxial construction, with dashed lines for the virtual extensions. The image distance from the centre is $CI = 10 - 7 = 3$ cm towards side A .



Refraction at the right surface; dashed backward extensions meet at virtual image I .

Step 4: Conclusion $v = -10$ cm. The bubble appears as a **virtual image**, 10 cm inside the surface B , or 3 cm to the left of C , towards A .

Quick Tip to Solve: From side B , first use $BP = 7 + 1.75$, and take both u and R negative; using $7 - 1.75$ solves the wrong viewing geometry.

27. (a) Use Ampere's law to derive the expression for the magnetic field due to a long straight current carrying wire of infinite length.

(b) Why is Ampere's law used for the derivation in (a) above and not Biot-Savart's law? Explain.

[3 marks]

Solution:

Concept:

- For a steady current, Ampere's circuital law in free space is $\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{\text{enclosed}}$, where μ_0 is the permeability of free space.
- An infinitely long straight wire has cylindrical symmetry. Its magnetic field is tangential to circles

centred on the wire, and its magnitude depends only on the perpendicular distance r from it.

Step 1: (a) Choose a circular Amperian loop Let the wire carry a steady current I . Choose a circle of radius r , centred on the wire, in a plane perpendicular to it. By cylindrical symmetry, B has the same value everywhere on this circle. The field is tangential to the loop, so choose the direction of traversal along $\vec{B}$. The angle between $\vec{B}$ and each path element $d\vec{l}$ is then zero. The right-hand thumb rule fixes the circulation direction: the thumb points along current and the curled fingers along the field.

Step 2: (a) Evaluate the circulation The chosen loop encloses the full wire current I . Applying Ampere's law,

$$\oint \vec{B} \cdot d\vec{l} = \oint B dl \cos 0 = \mu_0 I,$$
$$B \oint dl = \mu_0 I,$$
$$B(2\pi r) = \mu_0 I.$$

We can take B outside the integral only because symmetry makes its magnitude constant on this path. The path integral of dl is the circumference $2\pi r$. Thus the field decreases inversely with distance from the wire.

Step 3: (b) Explain the preference for Ampere's law Ampere's law is especially convenient here because a circular loop has constant B and the field is everywhere parallel to $d\vec{l}$. The calculation therefore reduces immediately to an algebraic equation. Biot-Savart's law is also valid and gives exactly the same result; it is not forbidden for an infinite wire. However, it requires summing contributions from all current elements along the wire by integration from $-\infty$ to $+\infty$, keeping track of their distances and angles. The reason for choosing Ampere's law is the simpler calculation made possible by the high symmetry, not any failure of Biot-Savart's law.

Step 4: Conclusion At perpendicular distance r , $B = \frac{\mu_0 I}{2\pi r}$, directed tangentially by the right-hand thumb rule. Ampere's law is preferred for its simplicity in this symmetric geometry; Biot-Savart's law remains applicable.

Quick Tip to Solve: Before taking B outside an Amperian integral, identify a path on which both its magnitude and its angle with $d\vec{l}$ are constant.

28. Differentiate between half-wave and full-wave rectification. With the help of a circuit diagram, explain the working of a full-wave rectifier. [3 marks]

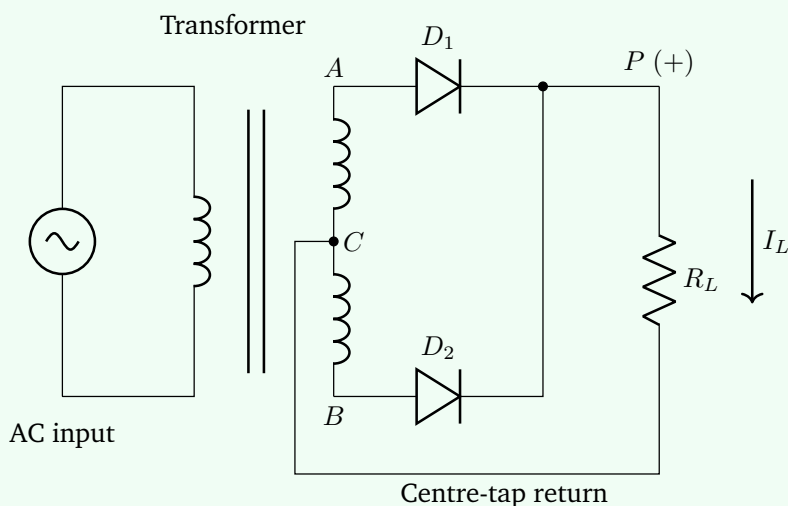
Solution:

Concept:

- Rectification converts alternating current into unidirectional current. A p-n junction diode conducts when forward biased and blocks current when reverse biased, in the ideal approximation.
- In a centre-tapped full-wave rectifier, the two equal halves of the transformer secondary provide voltages of opposite polarity relative to the centre tap, so two diodes conduct alternately.

Step 1: Compare the two kinds of rectification A half-wave rectifier uses only one half-cycle of each input cycle; its output is zero during the other half-cycle. A simple half-wave circuit uses one diode, and the ripple frequency equals the input frequency f . A full-wave rectifier uses both half-cycles, giving current through the load in the same direction during each half-cycle. Its ripple frequency is $2f$, its average output is larger for the same peak load voltage, and its output is easier to smooth. The centre-tapped version shown here uses two diodes.

Step 2: Connect the centre-tapped rectifier Connect secondary ends A and B to the anodes of diodes D_1 and D_2 . Join their cathodes at P , the positive output terminal. Connect the load resistance R_L between P and the centre tap C . The transformer primary receives the alternating input. The centre tap provides the return path for both diode currents.



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

Step 3: Follow the first half-cycle When A is positive relative to C , B is negative relative to C . Thus D_1 is forward biased and D_2 is reverse biased. Conventional current follows $A \rightarrow D_1 \rightarrow P \rightarrow R_L \rightarrow C$, returning through the upper half of the secondary winding.

Step 4: Follow the second half-cycle When the input reverses, B becomes positive and A negative relative to C . Now D_2 conducts and D_1 blocks. Current follows $B \rightarrow D_2 \rightarrow P \rightarrow R_L \rightarrow C$, returning through the lower half of the secondary. Current through R_L therefore still flows from P towards C .

Step 5: Conclusion Half-wave rectification uses one half-cycle, whereas full-wave rectification uses both. Alternate conduction of D_1 and D_2 produces a unidirectional, pulsating output across R_L , with two pulses per input cycle; an additional filter would be needed for a nearly steady output.

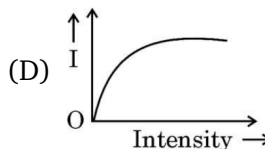
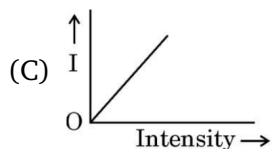
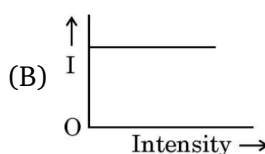
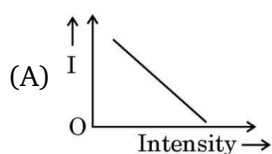
Quick Tip to Solve: Trace each conducting diode's path through the load: both paths must enter the same end of R_L , while the other diode is reverse biased.

Section D (8 marks)

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

29. Einstein explained photoelectric effect on the basis of Planck's quantum theory, where light travels in the form of small bundles of energy called photons. The energy of each photon is $h\nu$, where ν is the frequency of incident light and h is Planck's constant. The number of photons in a beam of light determines the intensity of the incident light. A photon incident on a metal surface transfers its total energy $h\nu$ to a free electron in the metal. A part of this energy is used in ejecting the electron from the metal and is called its work function. The rest of the energy is carried by the ejected electron as its kinetic energy. [4 marks]

29(i). (i) Which of the following graphs shows the variation of photoelectric current I with the intensity of light? [1 mark]



Correct Answer: (C)

Solution:

Concept:

- For a fixed incident frequency above the threshold, increasing light intensity increases the number of photons reaching the metal per second and hence the rate of photoelectron emission.
- Photocurrent is $I = e\dot{N}_e$, where e is the electronic charge magnitude and $\dot{N}_e$ is the number of electrons collected per second.

Step 1: Relate current to intensity With the metal, frequency and collecting conditions unchanged, the collected electron rate is proportional to the intensity of incident light. Thus I rises linearly with intensity and is zero when the illumination is zero, neglecting dark current.

Step 2: Compare the printed graphs Graph (C) is a straight line of positive slope through the origin. Graph (A) instead decreases and graph (B) stays constant. Graph (D) bends towards saturation; saturation with increasing collecting potential must not be confused with variation with light intensity.

Step 3: Conclusion The required relation is $I \propto \text{intensity}$, represented by graph (C). Hence, the correct option is (C).

Quick Tip to Solve: Check the horizontal axis first: current versus intensity is linear, whereas current versus collecting potential may saturate.

29(ii). (ii) When the frequency of the incident light is increased without changing its intensity, the saturation current:

[1 mark]

- (A) increases linearly
- (B) decreases
- (C) increases non-linearly
- (D) remains the same

Correct Answer: (D) remains the same

Solution:

Concept:

- Saturation current is reached when all emitted photoelectrons are collected. It measures the electron emission rate, rather than their maximum kinetic energy.
- Einstein's photoelectric equation is $K_{\max} = h\nu - \phi$, where ϕ is the metal's work function. Frequency controls the energy available to each emitted electron.

Step 1: Apply the intensity convention of the passage The passage associates intensity with the number of incident photons. Under the CBSE relation used here, unchanged intensity leaves the number of emitted photoelectrons per second, and hence the saturation current, unchanged, provided the incident frequency is above threshold.

Step 2: Separate electron rate from electron energy Increasing frequency raises $h\nu$, so it raises $K_{\max}$ and the stopping potential. It does not increase the saturation current in this stated treatment. The options predicting a linear increase, a nonlinear increase or a decrease confuse a change in electron energy with a change in emission rate.

Step 3: Conclusion At unchanged intensity, the saturation current remains the same in the photoelectric relation used by the passage. Hence, the correct option is (D).

Quick Tip to Solve: For this case study, pair intensity with saturation current and frequency with maximum kinetic energy or stopping potential.

29(iii). (iii) Which of the following graphs can be used to obtain the value of Planck's constant?

[1 mark]

- (A) Photocurrent versus Intensity of incident light
- (B) Photocurrent versus Frequency of incident light
- (C) Cut-off potential versus Frequency of incident light
- (D) Cut-off potential versus Intensity of incident light

Correct Answer: (C) Cut-off potential versus Frequency of incident light

Solution:

Concept:

- At the cut-off or stopping potential V_0 , the retarding electric field stops even the fastest photoelectrons, so $eV_0 = K_{\max}$.
- Einstein's equation gives $K_{\max} = h\nu - \phi$, where h is Planck's constant, ν is the light frequency and ϕ is the metal's work function.

Step 1: Express stopping potential in linear form Combining the two energy relations and dividing by

the positive electronic charge magnitude e gives

$$V_0 = \frac{h}{e}\nu - \frac{\phi}{e}.$$

This has the straight-line form $y = mx + b$, with V_0 on the vertical axis and frequency on the horizontal axis.

Step 2: Identify the measurable slope The slope of the cut-off-potential versus frequency graph is $m = h/e$, so multiplying it by e gives Planck's constant. Photocurrent graphs concern the electron collection rate, and varying intensity does not provide this stopping-potential slope.

Step 3: Conclusion Use the cut-off potential versus frequency graph and calculate $h = e \Delta V_0 / \Delta \nu$. Hence, the correct option is (C).

Quick Tip to Solve: A stopping-potential versus frequency slope is h/e ; a maximum-kinetic-energy versus frequency slope is h .

29(iv)(a). Red light, yellow light and blue light of the same intensity are incident on a metal surface successively. K_R , K_Y and K_B represent the maximum kinetic energy of photoelectrons respectively, then: [1 mark]

- (A) $K_R > K_Y > K_B$
- (B) $K_Y > K_B > K_R$
- (C) $K_B > K_Y > K_R$
- (D) $K_R > K_B > K_Y$

Correct Answer: (C) $K_B > K_Y > K_R$

Solution:

Concept:

- Einstein's photoelectric equation is $K_{\max} = h\nu - \phi$, where h is Planck's constant, ν is the light frequency and ϕ is the work function of the metal.
- For the same metal, ϕ is fixed. Provided photoelectrons are emitted, their maximum kinetic energy increases with frequency, not intensity.

Step 1: Compare the frequencies Blue light has a shorter wavelength than yellow light, and yellow has a shorter wavelength than red. Since $\nu = c/\lambda$, where c is the speed of light, the frequency order is $\nu_B > \nu_Y > \nu_R$.

Step 2: Apply the same work function The question refers to photoelectrons from all three colours, so emission is understood to occur for each. Multiplying the frequency order by positive h and subtracting the same ϕ preserves the order. Equal intensity does not make photon energies equal. Option (A) reverses the frequency order; (B) wrongly puts yellow above blue; (D) wrongly puts red above blue and yellow.

Step 3: Conclusion $K_B > K_Y > K_R$. Hence, the correct option is (C).

Quick Tip to Solve: For one emitting metal, rank maximum kinetic energies by colour frequency: blue, yellow, then red.

29(iv)(b). Which of the following metals exhibits photoelectric effect with visible light?

[1 mark]

- (A) Caesium
- (B) Zinc
- (C) Cadmium
- (D) Magnesium

Correct Answer: (A) Caesium

Solution:

Concept:

- Photoelectric emission occurs when the incident photon energy $h\nu$ is at least the metal's work function ϕ , the minimum energy needed to remove an electron.
- A smaller work function means a lower threshold frequency $\nu_0 = \phi/h$. Alkali metals such as caesium can therefore emit electrons under suitable visible light.

Step 1: Identify the low-work-function metal Caesium has a small work function, about 2 eV. Photons from a suitable portion of the visible spectrum have enough energy to overcome this barrier and eject electrons. Thus visible light can produce photoelectric emission from caesium.

Step 2: Exclude the other metals Zinc, cadmium and magnesium have substantially higher work functions. Visible photons do not supply the required threshold energy for these metals in the usual photoelectric-effect treatment; ultraviolet radiation is needed. Increasing visible-light intensity cannot compensate for an individual photon's insufficient energy.

Step 3: Conclusion Caesium exhibits the photoelectric effect with suitable visible light. Hence, the correct option is (A).

Quick Tip to Solve: For visible-light photoemission, look for a low-work-function alkali metal such as caesium.

30. A galvanometer is an instrument used to show the direction and strength of the current passing through it. In a galvanometer, a coil placed in a magnetic field experiences a torque and hence gets deflected when a current passes through it. The name is derived from the surname of Italian scientist L. Galvani, who in 1791 discovered that electric current makes a dead frog's leg jerk. A spring attached with the coil provides a counter torque. In equilibrium, the deflecting torque is balanced by the restoring torque of the spring and we have: $NBAI = k\phi$, where N is the total number of turns in the coil, A is the area of cross-section of each turn, B is the radial magnetic field, k is the torsional constant of the spring, ϕ is the angular deflection of the coil. As the current (I_g) which produces full scale deflection in the galvanometer is very small, the galvanometer cannot as such be used to measure current in electric circuits. A small resistance, called shunt, of a suitable value is connected with the galvanometer to convert it into an ammeter of desired range. By using a higher resistance, a galvanometer can also be converted into a voltmeter. [4 marks]

30(i). (i) The value of the current sensitivity of a galvanometer is given by: [1 mark]

- (A) $\frac{k}{NBA}$
 (B) $\frac{NBA}{k}$
 (C) $\frac{kBA}{N}$
 (D) $\frac{kNB}{A}$

Correct Answer: (B) $\frac{NBA}{k}$

Solution:

Concept:

- Current sensitivity is the angular deflection per unit current: $S_I = \phi/I$, measured in rad A^{-1} .
- In a radial magnetic field, the deflecting torque $NBAI$ balances the spring torque $k\phi$. Here N is the number of turns, B the field, A the coil area and k the torsional constant.

Step 1: Apply torque balance At steady deflection, the net torque on the coil is zero. Thus

$$NBAI = k\phi.$$

Divide both sides by kI to isolate the deflection produced by unit current.

Step 2: Identify the sensitivity and reject the alternatives The ratio is $\phi/I = NBA/k$. A stronger field or a larger number of turns increases the deflection, while a stiffer spring decreases it. Option (A) is the reciprocal, giving current per unit deflection. Options (C) and (D) put k in the numerator and therefore incorrectly predict that a stiffer spring increases sensitivity.

Step 3: Conclusion The current sensitivity is $S_I = \frac{NBA}{k}$. Hence, the correct option is (B).

Quick Tip to Solve: Write sensitivity as output divided by input: current sensitivity is deflection divided by current, not its reciprocal.

30(ii). (ii) A galvanometer of resistance $6\ \Omega$ shows full scale deflection for a current of $0.2\ \text{A}$. The value of shunt to be used with this galvanometer to convert it into an ammeter of range $(0 - 5\ \text{A})$ is: [1 mark]

- (A) $0.25\ \Omega$
- (B) $0.30\ \Omega$
- (C) $0.50\ \Omega$
- (D) $6.0\ \Omega$

Correct Answer: (A) $0.25\ \Omega$

Solution:

Concept:

- A low shunt resistance S is connected in parallel with galvanometer resistance G , so most of the total current bypasses the delicate coil.
- At full scale the coil carries I_g , the shunt carries $I - I_g$, and equal parallel voltages give $I_g G = (I - I_g)S$.

Step 1: Determine the shunt current Here $G = 6\ \Omega$, $I_g = 0.2\ \text{A}$ and the desired full-scale current is $I = 5\ \text{A}$. Current conservation at the parallel junction gives

$$I_s = I - I_g = 5 - 0.2 = 4.8\ \text{A}.$$

The full $5\ \text{A}$ does not flow through the shunt because the coil takes $0.2\ \text{A}$.

Step 2: Use the equal voltage across both branches The voltage across the galvanometer, and hence the shunt, is $I_g G = 0.2 \times 6 = 1.2\ \text{V}$. Therefore

$$S = \frac{I_g G}{I_s} = \frac{1.2}{4.8} = 0.25\ \Omega.$$

At $4.8\ \text{A}$, the other proposed shunts $0.30\ \Omega$, $0.50\ \Omega$ and $6.0\ \Omega$ would have voltage drops $1.44\ \text{V}$, $2.4\ \text{V}$ and $28.8\ \text{V}$, respectively. None equals the coil voltage required for full scale.

Step 3: Conclusion Connect a shunt of resistance $0.25\ \Omega$ in parallel with the galvanometer. Hence, the correct option is (A).

Quick Tip to Solve: In the shunt formula, subtract the galvanometer current from the desired range before dividing: $S = I_g G / (I - I_g)$.

30(iii). (iii) The value of resistance of the ammeter in case (ii) will be:

[1 mark]

- (A) $0.20\ \Omega$
- (B) $0.24\ \Omega$
- (C) $6.0\ \Omega$
- (D) $6.25\ \Omega$

Correct Answer: (B) $0.24\ \Omega$

Solution:

Concept:

- The converted ammeter consists of galvanometer resistance G and shunt resistance S in parallel, so $R_A = GS/(G + S)$.
- The resistance of the complete instrument is also its terminal voltage divided by the total current: $R_A = V/I$.

Step 1: Combine the two parallel resistances From case (ii), $G = 6\ \Omega$ and $S = 0.25\ \Omega$. Therefore

$$R_A = \frac{6 \times 0.25}{6 + 0.25} = \frac{1.5}{6.25} = 0.24\ \Omega.$$

Both branches contribute to the current, so the instrument resistance is lower than either branch resistance.

Step 2: Check using full-scale voltage and current At full scale the voltage is $V = I_g G = 0.2 \times 6 = 1.2\text{ V}$, while the total ammeter current is 5 A . Hence $V/I = 1.2/5 = 0.24\ \Omega$, confirming the parallel calculation. Option (A) does not satisfy this ratio; option (C) ignores the shunt; option (D) adds resistances as if they were in series.

Step 3: Conclusion The resistance of the ammeter is $R_A = 0.24\ \Omega$. Hence, the correct option is (B).

Quick Tip to Solve: Once the range is known, use $R_A = I_g G/I$; the total ammeter resistance must be smaller than its shunt resistance.

30(iv)(a). A galvanometer is converted into a voltmeter of range $(0 - V)$ by connecting with it, a resistance R_1 . If R_1 is replaced by R_2 , the range becomes $(0 - 2V)$. The resistance of the galvanometer is:

[1 mark]

- (A) $(R_2 - 2R_1)$
- (B) $(R_2 - R_1)$
- (C) $(R_1 + R_2)$
- (D) $(R_1 - 2R_2)$

Correct Answer: (A) $(R_2 - 2R_1)$

Solution:

Concept:

- A galvanometer becomes a voltmeter when a resistance is connected in series with its coil. At the limiting voltage, the coil carries its full-scale current I_g .
- If the coil resistance is G and the series resistance is R , the voltage range is $V_{\max} = I_g(G + R)$. The same coil has the same G and I_g for both ranges.

Step 1: Write the equations for the two ranges The first series resistance is R_1 , while replacing it by R_2 doubles the limiting voltage. Applying Ohm's law to the entire series combination gives

$$V = I_g(G + R_1), \quad 2V = I_g(G + R_2).$$

The galvanometer resistance must be included in both equations; the stated resistances are only the external series resistances.

Step 2: Eliminate the full-scale current Divide the second equation by the first and rearrange:

$$2 = \frac{G + R_2}{G + R_1}, \quad 2G + 2R_1 = G + R_2.$$

Subtracting one G from each side isolates the coil resistance. The difference $R_2 - R_1$ alone omits the first series resistance still present in the doubled total. The sum in (C) and the reversed coefficients in (D) do not satisfy these range equations.

Step 3: Conclusion The resistance of the galvanometer is $G = R_2 - 2R_1$. Hence, the correct option is (A).

Quick Tip to Solve: When a voltmeter range doubles, double the total series resistance, including the galvanometer coil resistance.

OR

30(iv)(b). A current of 5 mA flows through a galvanometer. Its coil has 100 turns, each of area of cross-section 18 cm^2 and is suspended in a magnetic field 0.20 T. The deflecting torque acting on the coil will be: [1 mark]

- (A) $3.6 \times 10^{-3} \text{ Nm}$
- (B) $1.8 \times 10^{-4} \text{ Nm}$
- (C) $2.4 \times 10^{-3} \text{ Nm}$
- (D) $1.2 \times 10^{-4} \text{ Nm}$

Correct Answer: (B) $1.8 \times 10^{-4} \text{ Nm}$

Solution:

Concept:

- The deflecting torque on a moving-coil galvanometer in a radial magnetic field is $\tau = NBAI$, where N is the number of turns, B the magnetic field, A the area of each turn and I the current.
- Use SI units in this expression: $1 \text{ mA} = 10^{-3} \text{ A}$ and $1 \text{ cm}^2 = 10^{-4} \text{ m}^2$. Torque is measured in N m.

Step 1: Convert current and area to SI units The given coil has $N = 100$ turns in a field $B = 0.20 \text{ T}$. Its current and the area of each turn are

$$I = 5 \times 10^{-3} \text{ A}, \quad A = 18 \times 10^{-4} \text{ m}^2.$$

The conversion factor for area must be squared because a square centimetre is $(10^{-2} \text{ m})^2$.

Step 2: Evaluate the magnetic torque In the radial field, the coil plane remains parallel to the field,

so the torque factor is unity at every deflection. Substitution gives

$$\begin{aligned}\tau &= 100(0.20)(18 \times 10^{-4})(5 \times 10^{-3}) \\ &= 1800 \times 10^{-7} \text{ N m.}\end{aligned}$$

Express this product in standard scientific notation before comparing the options. The other listed values do not equal the product of the four given quantities; in particular, a square-centimetre conversion cannot use 10^{-2} .

Step 3: Conclusion The deflecting torque is $1.8 \times 10^{-4} \text{ N m}$. Hence, the correct option is (B).

Quick Tip to Solve: For galvanometer torque, convert the coil area with 10^{-4} and the current with 10^{-3} before multiplying by NB .

Section E (15 marks)

31(a). (i) Define self-inductance of a coil. Derive the expression for the energy required to build up a current I in a coil of self-inductance L .

(ii) The currents passing through two inductors of self-inductances 10 mH and 20 mH increase with time at the same rate. Draw graphs showing the variation of:

(I) the magnitude of emf induced with the rate of change of current in each inductor.

(II) the energy stored in each inductor with the current flowing through it.

[5 marks]

Solution:

Concept:

- For a linear coil, the magnetic flux linkage is $N\Phi = Li$, where N is the number of turns, Φ the flux through each turn, i the current and L the self-inductance.
- Faraday's law gives the self-induced emf $\varepsilon = -L di/dt$. Its sign expresses opposition to the change of current; its magnitude is $L|di/dt|$.
- The work done against the induced emf is stored in the coil's magnetic field. For constant L , the energy at current I is $U = \frac{1}{2}LI^2$.

Step 1: (i) Define the self-inductance Self-inductance of a coil is the magnetic flux linkage per unit current flowing through it:

$$L = \frac{N\Phi}{i}.$$

Equivalently, its numerical value is the magnitude of the induced emf when the current changes at unit rate. A coil has self-inductance 1 H if an emf of 1 V is induced when its current changes at 1 A s^{-1} . We assume a linear coil, so its inductance remains constant as the current is increased.

Step 2: (i) Derive the energy required to establish the current Let the instantaneous current be i , increasing by di in time dt . The induced emf opposes this increase, so the external source must supply a potential difference $V_L = L di/dt$ across the inductive part. Charge $dq = i dt$ passes through the coil in that interval. The work done against the induced emf is therefore

$$\begin{aligned}dW &= V_L dq \\ &= \left(L \frac{di}{dt} \right) i dt = Li di.\end{aligned}$$

Starting with zero current and integrating up to the final current I ,

$$W = \int_0^I Li \, di = L \left[\frac{i^2}{2} \right]_0^I = \frac{1}{2} LI^2.$$

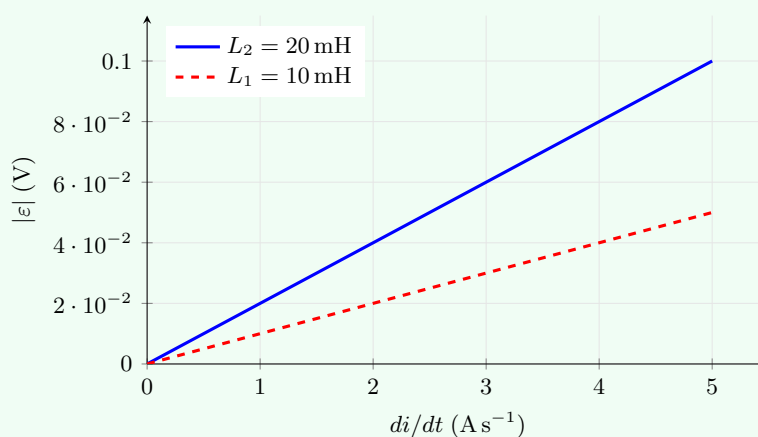
This energy is stored in the magnetic field: $U = W$. The expression is the energy needed for magnetic-field buildup in an ideal inductor; if the coil has resistance, the source must additionally supply the energy dissipated as heat.

Step 3: (ii)(I) Plot induced-emf magnitude against current-change rate Put $x = di/dt \geq 0$, since the currents are increasing. With $L_1 = 10 \text{ mH} = 0.010 \text{ H}$ and $L_2 = 20 \text{ mH} = 0.020 \text{ H}$,

$$|\varepsilon_1| = (0.010 \text{ H})x,$$

$$|\varepsilon_2| = (0.020 \text{ H})x.$$

Both graphs are straight lines through the origin. Their slopes equal the respective inductances, so the 20 mH line is twice as steep. At any common positive rate of change of current, $|\varepsilon_2| = 2|\varepsilon_1|$. The plotted range is illustrative; these relations hold throughout the linear regime.



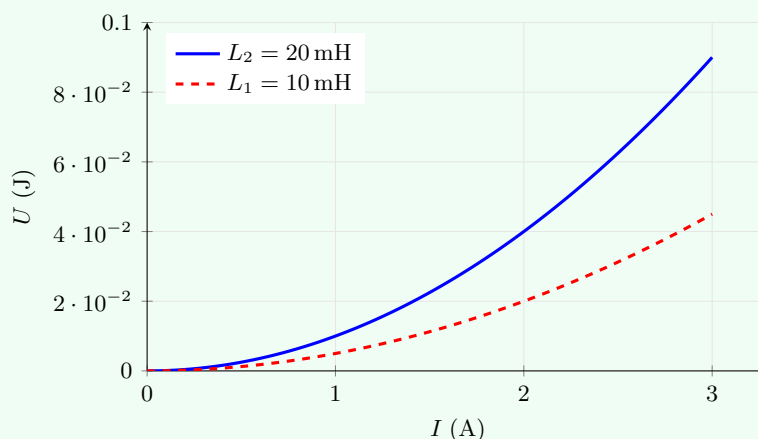
Induced-emf magnitude versus rate of increase of current; slope equals inductance.

Step 4: (ii)(II) Plot magnetic energy against current Using $U = \frac{1}{2} LI^2$, the two energy-current relations are

$$U_1 = (0.005 \text{ H})I^2,$$

$$U_2 = (0.010 \text{ H})I^2.$$

For positive current, both curves are upward-opening parabolas starting at the origin with zero initial slope. At each common nonzero current, the 20 mH coil stores twice the energy of the 10 mH coil, so its curve lies above the other. For example, at $I = 2 \text{ A}$, their energies are 0.020 J and 0.040 J, respectively. Equal rates of increase refer to the first graph; the second graph compares energies at the same current.



Magnetic energy versus current; both curves are parabolas.

Step 5: Conclusion Self-inductance is $L = N\Phi/i$, and the magnetic energy required to build current I is $U = \frac{1}{2}LI^2$. The emf-rate graphs are straight lines through the origin, whereas the energy-current graphs are parabolas. In both comparisons the 20 mH inductor gives twice the ordinate of the 10 mH inductor at the same abscissa.

Quick Tip to Solve: Read the horizontal axis before sketching: $|\varepsilon|$ versus di/dt is linear, but U versus I is quadratic. Doubling L doubles every vertical value on either graph.

OR

- 31(b).** (i) Define the term mutual inductance. Deduce the expression for the mutual inductance of two long coaxial solenoids of the same length having different radii and different number of turns.
 (ii) The current through an inductor is uniformly increased from zero to 2 A in 40 s. An emf of 5 mV is induced during this period. Find the flux linked with the inductor at $t = 10$ s. [5 marks]

Solution:

Concept:

- Mutual inductance M is the flux linkage of one coil per unit current in the other: $N_2\Phi_{21} = MI_1$. Here Φ_{21} is the magnetic flux through each turn of coil 2 due to current I_1 in coil 1.
- A long air-core solenoid produces an approximately uniform internal field $B = \mu_0 nI$, where $n = N/\ell$ is its number of turns per unit length; its external field is negligible.
- For an inductor of constant self-inductance L , total flux linkage is $\lambda = N\Phi = LI$, and induced emf is $\varepsilon = -d\lambda/dt = -L dI/dt$. The minus sign expresses opposition to the change in current.

Step 1: (i) Define mutual inductance and its unit Mutual inductance of two coils is the magnetic flux linkage with either coil produced by unit current in the other coil. Equivalently, its magnitude is the emf induced in either coil when the current in the other changes at unit rate:

$$M = \frac{N_2\Phi_{21}}{I_1}, \quad \varepsilon_2 = -M \frac{dI_1}{dt}.$$

Its SI unit is the henry (H). 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: Identify the common flux area Consider two long coaxial air-core solenoids with common

length ℓ , radii $r_1 < r_2$, and total turns N_1 and N_2 , respectively. Their turn densities are $n_1 = N_1/\ell$ and $n_2 = N_2/\ell$. Neglect end effects. The smaller cross-sectional area is $A_1 = \pi r_1^2$. When current flows in the inner solenoid, its field is essentially confined to this smaller area, so the flux through an outer turn must be calculated using A_1 , even though the outer turn encloses a larger area.

Step 3: Derive the flux linkage and mutual inductance Let the inner solenoid carry current I_1 . The field it produces and the flux through each turn of the outer solenoid are

$$B_1 = \mu_0 \frac{N_1}{\ell} I_1, \quad \Phi_{21} = B_1 A_1.$$

There are N_2 outer turns linked with this flux. Thus

$$N_2 \Phi_{21} = N_2 B_1 A_1 = \frac{\mu_0 N_1 N_2 A_1}{\ell} I_1, \\ M_{21} = \frac{N_2 \Phi_{21}}{I_1} = \frac{\mu_0 N_1 N_2 A_1}{\ell} = \mu_0 n_1 n_2 A_1 \ell.$$

To check the reverse coupling, current I_2 in the outer solenoid creates $B_2 = \mu_0 N_2 I_2 / \ell$ throughout the inner solenoid. Each inner turn intercepts area A_1 , giving $N_1 \Phi_{12} = N_1 B_2 A_1$, and hence the same value $M_{12} = M_{21}$. For a common uniform magnetic medium of permeability μ , replace μ_0 by μ .

Step 4: (ii) Calculate the inductance and current at ten seconds The current increases uniformly, so its rate of change is constant:

$$\frac{dI}{dt} = \frac{2 - 0}{40} = 0.05 \text{ A s}^{-1}.$$

Convert the induced emf to volts, $|\varepsilon| = 5 \times 10^{-3} \text{ V}$. Using magnitudes in the self-induction equation gives

$$L = \frac{|\varepsilon|}{dI/dt} = \frac{5 \times 10^{-3}}{0.05} = 0.10 \text{ H}.$$

Since the initial current is zero, the current after 10 s is

$$I(10) = 0.05 \times 10 = 0.50 \text{ A}.$$

Step 5: Determine the flux linked with the inductor The required linked flux is the total flux linkage, $\lambda = N\Phi$, rather than the flux through an individual turn. Starting with zero current gives zero initial self-flux linkage. Therefore

$$\lambda(10) = LI(10) = 0.10 \times 0.50 = 5.0 \times 10^{-2} \text{ Wb}.$$

Flux linkage may also be written in weber-turns, with turn count dimensionless. As a check, integrating the constant emf magnitude for ten seconds gives $\lambda(10) = |\varepsilon|t = (5 \times 10^{-3})(10)$, the same result. The flux per individual turn would require the number of turns, which is not given.

Step 6: Conclusion (i) For long coaxial air-core solenoids, $M = \mu_0 N_1 N_2 \pi r_1^2 / \ell = \mu_0 n_1 n_2 \pi r_1^2 \ell$, where r_1 is the smaller radius. (ii) At $t = 10 \text{ s}$, the flux linked with the inductor is $5.0 \times 10^{-2} \text{ Wb}$ (total flux linkage).

Quick Tip to Solve: Use the smaller solenoid's area for mutual inductance. For a constant induced emf and zero initial linkage, obtain the linked flux directly from $\lambda = |\varepsilon|t$.

- 32(a).** (i) Draw a ray diagram of a reflecting telescope (Cassegrain) and explain the formation of image. State two important advantages that a reflecting telescope has over a refracting telescope.
- (ii) In a refracting telescope, the focal length of the objective is 50 times the focal length of the eyepiece. When the final image is formed at infinity, the length of the tube is 102 cm. Find the focal lengths of the two lenses.

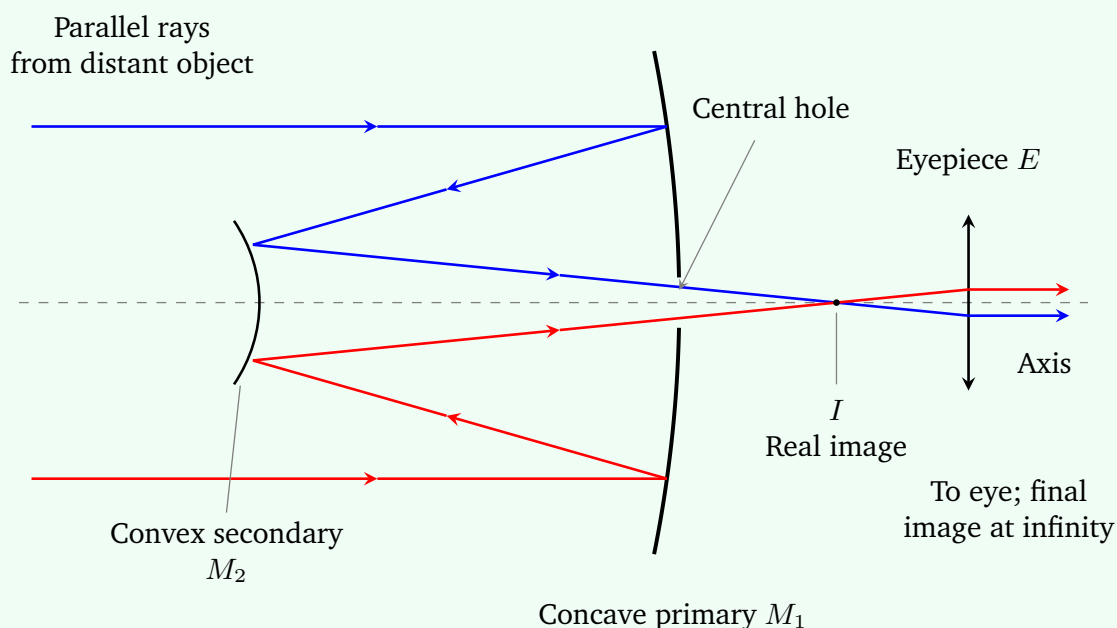
[5 marks]

Solution:

Concept:

- A Cassegrain telescope uses a large concave primary mirror and a small convex secondary mirror. Reflection focuses incident light without chromatic dispersion.
- In normal adjustment, the real image made by the objective system lies in the focal plane of the eyepiece; the eyepiece then gives a magnified angular view with the final virtual image at infinity.
- For a refracting astronomical telescope in normal adjustment, the tube length is $L = f_o + f_e$, where f_o and f_e are the positive focal lengths of its objective and eyepiece.

Step 1: (i) Trace the rays through the two mirrors Parallel rays from a distant object fall on the large concave primary mirror M_1 . After reflection they travel towards its principal focus. Before reaching that focus, they meet the small convex secondary mirror M_2 , placed in front of the primary. This secondary reflects them back towards the primary, through a central hole in it. The rays converge to form a real intermediate image I behind the primary. The diagram shows a representative axial bundle; different distant object points form the extended intermediate image.



Cassegrain telescope: ray path through the perforated primary to the eyepiece (schematic).

Step 2: Explain the eyepiece and the two advantages The eyepiece E acts as a magnifier for the intermediate image. When I lies in its first focal plane, rays emerging from E are parallel and the final virtual image is at infinity. Thus the mirrors collect light and form the real image, while the eyepiece increases the angular size seen by the eye.

Advantage 1: Absence of chromatic aberration in the mirror objective. Reflection does not separate the different colours as a refracting objective does, so their focal positions coincide.

Advantage 2: A much larger objective aperture is practical. A mirror can be supported from the back, whereas a large lens must be supported mainly at its rim. Large mirrors therefore provide

greater light-gathering power for faint objects and better resolving power for closely spaced objects.

Step 3: (ii) Apply the condition for normal adjustment Here the objective and eyepiece are both lenses. Since the final image is at infinity, the real image formed at the objective's focal plane must also lie in the eyepiece's first focal plane. The separation between the lenses is therefore the sum of their focal lengths, not their difference. Using the stated ratio,

$$f_o = 50f_e, \quad L = f_o + f_e = 102 \text{ cm}.$$

Substitute the first equation into the second:

$$50f_e + f_e = 102 \text{ cm}, \quad 51f_e = 102 \text{ cm}.$$

Step 4: Calculate and check both focal lengths Dividing the tube length into the ratio 50 : 1 gives

$$f_e = \frac{102}{51} \text{ cm} = 2 \text{ cm},$$
$$f_o = 50(2 \text{ cm}) = 100 \text{ cm}.$$

The values satisfy both given conditions: their sum is 102 cm, and the objective focal length is exactly fifty times that of the eyepiece.

Step 5: Conclusion The Cassegrain arrangement forms a real image behind its perforated primary mirror, viewed through an eyepiece. Its mirror objective avoids chromatic aberration and permits a large aperture. For the refracting telescope, $f_o = 100 \text{ cm}, \quad f_e = 2 \text{ cm}$.

Quick Tip to Solve: For a refracting telescope at normal adjustment, combine $L = f_o + f_e$ with the given focal-length ratio: here the tube length contains $50 + 1 = 51$ equal parts.

OR

32(b). (i) Write any two advantages of a compound microscope over a simple microscope. Draw a ray diagram for the image formation at the near point by a compound microscope and explain it.

(ii) A thin planoconcave lens with its curved face of radius of curvature R is made of glass of refractive index n_1 . It is placed coaxially in contact with a thin equiconvex lens of same radius of curvature of refractive index n_2 . Obtain the power of the combination lens. [5 marks]

Solution:

Concept:

- A compound microscope uses a short-focal-length objective to form a real enlarged intermediate image and an eyepiece to magnify that image further. Its magnifying power is the product of the objective's linear magnification and the eyepiece's angular magnification.
- For the final image at the near point, the intermediate image lies between the eyepiece and its first principal focus. The eyepiece then produces a virtual enlarged image at the least distance of distinct vision D , normally 25 cm.
- For a thin lens in air, the lens-maker formula is $P = 1/f = (n - 1)(1/R_1 - 1/R_2)$. Here n is its refractive index and the radii have Cartesian signs. Powers of thin lenses in contact add.

Step 1: (i) State two advantages First, a compound microscope provides much greater magnification

than a simple microscope because enlargement occurs in two stages: the objective forms an enlarged image and the eyepiece magnifies it again. Second, with a suitable high-numerical-aperture objective, it has greater resolving power, so it can distinguish much finer details and more closely spaced points in a specimen. Resolution is distinct from merely making a blurred image look larger.

Step 2: (i) Form the intermediate image with the objective Place the small object AB just beyond the objective's first focus F_o . The objective O forms a real, inverted and magnified image $A'B'$ inside the tube. In the diagram, a ray from B parallel to the principal axis is refracted through F'_o ; another passes undeviated through the objective's optical centre. Their intersection gives B' . Adjust the lens separation so that $A'B'$ lies between the eyepiece's first focus F_e and the eyepiece E .

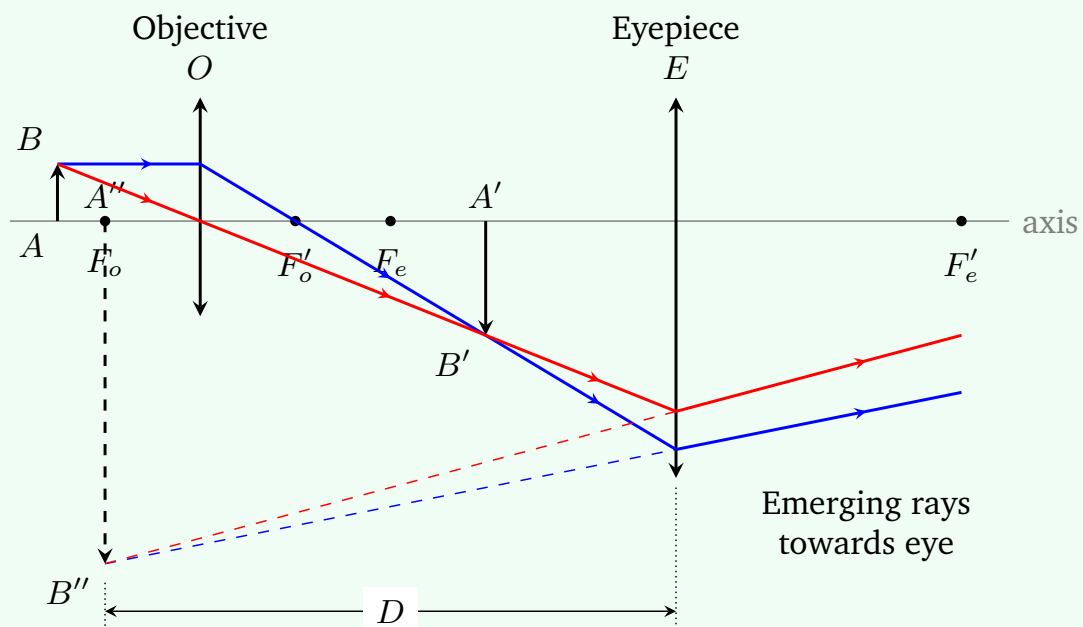
Step 3: (i) Produce the final image at the near point Beyond B' , the rays spread out and enter the eyepiece. Since the intermediate object is inside the eyepiece's focal length, the emerging rays diverge; their backward extensions meet at B'' . Thus $A''B''$ is virtual and enlarged relative to $A'B'$, and inverted relative to the original object AB . The eye is placed close to the eyepiece and the final image is adjusted to the near point. Taking the eye approximately at the eyepiece, $v_e = -D$. The thin-lens equation gives

$$-\frac{1}{D} - \frac{1}{u_e} = \frac{1}{f_e}, \quad |u_e| = \frac{Df_e}{D + f_e} < f_e.$$

The magnitude of the total magnifying power is consequently

$$|M| = \left| \frac{v_o}{u_o} \right| \left(1 + \frac{D}{f_e} \right),$$

where u_o, v_o are the objective's object and image distances. Dashed rays in the sketch are backward extensions, not paths carrying light.



Compound microscope adjusted for a final virtual image at the near point (schematic; eye close to the eyepiece).

Step 4: (ii) Calculate the power of each lens Take light travelling from left to right and let $R > 0$ denote the given radius magnitude. For the planoconcave lens, orient the plane face first: $R_1 = \infty$ and $R_2 = +R$. Therefore

$$P_1 = (n_1 - 1) \left(0 - \frac{1}{R} \right) = -\frac{n_1 - 1}{R}.$$

Reversing this lens does not change its power. For the equiconvex lens, the first centre of curvature is on the right and the second on the left, so $R_1 = +R$ and $R_2 = -R$. Hence

$$P_2 = (n_2 - 1) \left(\frac{1}{R} - \frac{1}{-R} \right) = \frac{2(n_2 - 1)}{R}.$$

Step 5: (ii) Add the powers for contact The lenses are thin and coaxial, with zero separation, so there is no separation correction. Their equivalent power is

$$\begin{aligned} P &= P_1 + P_2 \\ &= -\frac{n_1 - 1}{R} + \frac{2(n_2 - 1)}{R} \\ &= \frac{2n_2 - n_1 - 1}{R}. \end{aligned}$$

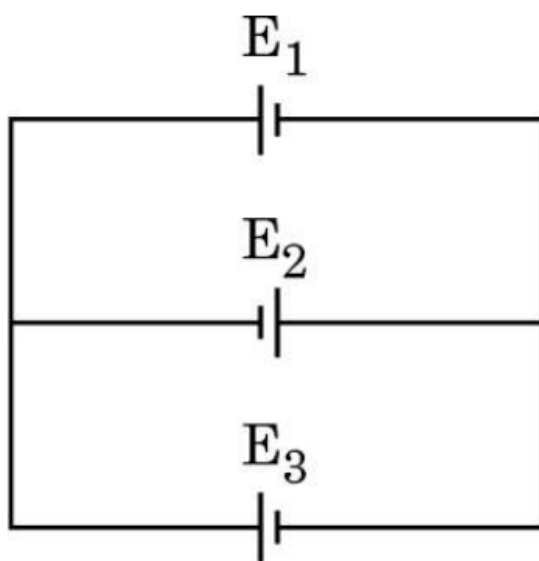
This expression is in dioptres when R is in metres. Its sign determines whether the combination converges or diverges; no numerical sign can be assigned without the refractive indices.

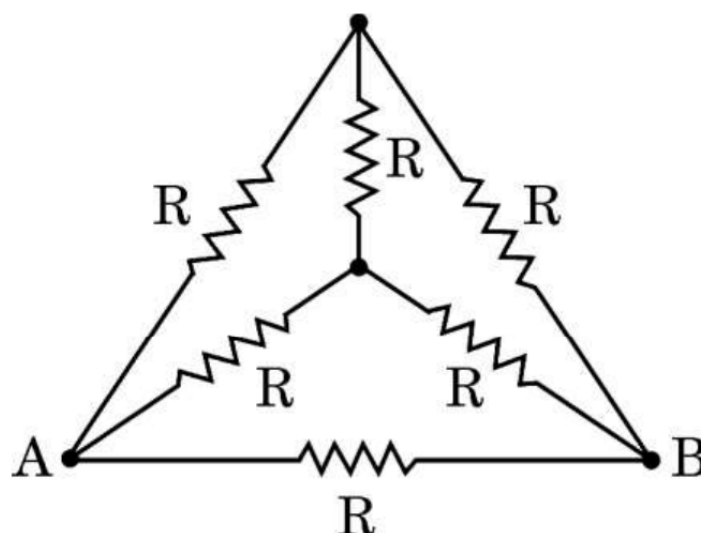
Step 6: Conclusion The compound microscope offers greater magnification and resolving power. For near-point viewing it forms a virtual, enlarged final image, inverted relative to the original object, at distance D . The lens combination has power $P = (2n_2 - n_1 - 1)/R$, in dioptres for R in metres.

Quick Tip to Solve: For near-point microscopy, put the intermediate image inside the eyepiece's focal length. For the lens pair, assign negative power to the planoconcave lens before adding the two powers.

33(a). (i) Three batteries E_1 , E_2 and E_3 of emfs and internal resistances $(4 \text{ V}, 2 \Omega)$, $(2 \text{ V}, 4 \Omega)$ and $(6 \text{ V}, 2 \Omega)$ respectively are connected as shown in the figure. Find the values of the currents passing through batteries E_1 , E_2 and E_3 .

(ii) The ends of six wires, each of resistance $R (= 10 \Omega)$ are joined as shown in the figure. The points A and B of the arrangement are connected in a circuit. Find the value of the effective resistance offered by it to the circuit. [5 marks]





Solution:

Concept:

- Kirchhoff's junction rule states that the algebraic sum of currents at an isolated junction is zero. The loop rule accounts for both the emf and the internal resistance of each battery.
- All three branches have the same terminal potential difference. The long line in a cell symbol denotes the positive terminal, so the middle battery has the opposite polarity to the other two.
- In a balanced resistor bridge, equipotential junctions carry no current through their connecting resistor. Series resistances add, while parallel branches obey $1/R_{eq} = \sum 1/R_i$.

Step 1: (i) Choose a common voltage and signed currents Call the left and right rails L and R , and put $V = V_L - V_R$. Initially take each branch current I_1, I_2, I_3 as positive from left to right. The printed symbols show the positive terminals of E_1 and E_3 on the left, and that of E_2 on the right. Traversing a branch from left to right therefore gives

$$V = 4 + 2I_1,$$

$$V = -2 + 4I_2,$$

$$V = 6 + 2I_3.$$

These equations include the voltage drops across the internal resistances; there is no external load branch.

Step 2: Apply the junction rule and calculate the branch currents Since no current enters or leaves the network externally, $I_1 + I_2 + I_3 = 0$. Substituting the branch expressions,

$$\frac{V - 4}{2} + \frac{V + 2}{4} + \frac{V - 6}{2} = 0.$$

Thus $2V - 8 + V + 2 + 2V - 12 = 0$, so $5V = 18$ and $V = 3.6\text{ V}$. The currents are

$$I_1 = \frac{3.6 - 4}{2} = -0.20\text{ A},$$

$$I_2 = \frac{3.6 + 2}{4} = 1.40\text{ A},$$

$$I_3 = \frac{3.6 - 6}{2} = -1.20\text{ A}.$$

A negative sign means right-to-left current through that battery. As a check, the two right-to-left currents total $0.20 + 1.20 = 1.40$ A, equal to the middle branch's left-to-right current.

Step 3: (ii) Identify the balanced bridge Denote the top vertex by C and the central junction by D . Along the two paths $A - C - B$ and $A - D - B$, the left and right resistances are equal:

$$\frac{R_{AC}}{R_{CB}} = \frac{R_{AD}}{R_{DB}} = 1.$$

Hence the bridge is balanced, $V_C = V_D$, and no current flows through the resistor CD . This resistor can be omitted when calculating the resistance between A and B .

Step 4: Combine the three conducting paths The direct path AB has resistance R ; each of $A - C - B$ and $A - D - B$ has resistance $2R$. These three paths are in parallel:

$$\frac{1}{R_{AB}} = \frac{1}{R} + \frac{1}{2R} + \frac{1}{2R} = \frac{2}{R}.$$

Therefore $R_{AB} = R/2$. With $R = 10\ \Omega$, this gives $R_{AB} = 5\ \Omega$.

Step 5: Conclusion (i) The currents through E_1, E_2, E_3 are respectively 0.20 A right to left, 1.40 A left to right, and 1.20 A right to left. (ii) The effective resistance is $5\ \Omega$.

Quick Tip to Solve: Read each battery's long plate before assigning its emf sign. For the six-wire network, first remove the zero-current bridge branch, then combine the remaining three paths.

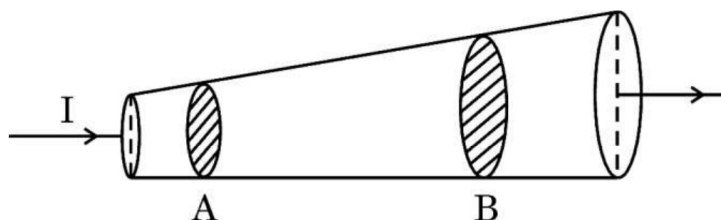
OR

33(b). (i) Current I ($= 1$ A) is passing through a copper rod ($n = 8.5 \times 10^{28}\ \text{m}^{-3}$) of varying cross-sections as shown in the figure. The areas of cross-section at points A and B along its length are $1.0 \times 10^{-7}\ \text{m}^2$ and $2.0 \times 10^{-7}\ \text{m}^2$ respectively. Calculate:

(I) the ratio of electric fields at points A and B .

(II) the drift velocity of free electrons at point B .

(ii) Two point charges q_1 ($= 16\ \mu\text{C}$) and q_2 ($= 1\ \mu\text{C}$) are placed at points $\vec{r}_1 = (3\ \text{m})\hat{i}$ and $\vec{r}_2 = (4\ \text{m})\hat{j}$. Find the net electric field $\vec{E}$ at point $\vec{r} = (3\ \text{m})\hat{i} + (4\ \text{m})\hat{j}$. [5 marks]



Solution:

Concept:

- In steady conduction the same current passes through every cross-section. Current density is $J = I/A$, and the local form of Ohm's law is $E = \rho J$, where ρ is the resistivity of copper.
- The drift speed satisfies $I = neAv_d$, where n is the free-electron number density, e is the magnitude of electronic charge, and A is the cross-sectional area. Electron drift is opposite to conventional current.
- The electric field of a point charge is $\vec{E} = kq\vec{R}/R^3$, where $\vec{R}$ points from the charge to the

observation point. Fields add as vectors, with $k = 9 \times 10^9 \text{ N m}^2\text{C}^{-2}$.

Step 1: (i)(I) Compare the local electric fields The material and hence resistivity are the same at A and B , while charge conservation keeps the current equal to 1 A at both sections. Thus $E = \rho I/A$, and

$$\frac{E_A}{E_B} = \frac{A_B}{A_A} = \frac{2.0 \times 10^{-7}}{1.0 \times 10^{-7}} = 2.$$

The narrower section requires twice the electric field to carry the same current, so the ratio is $E_A : E_B = 2 : 1$.

Step 2: (i)(II) Calculate the drift speed at B Use $A_B = 2.0 \times 10^{-7} \text{ m}^2$, $n = 8.5 \times 10^{28} \text{ m}^{-3}$, and $e = 1.6 \times 10^{-19} \text{ C}$. Solving the current relation for the drift speed gives

$$\begin{aligned} v_{dB} &= \frac{I}{neA_B} \\ &= \frac{1}{(8.5 \times 10^{28})(1.6 \times 10^{-19})(2.0 \times 10^{-7})} \\ &= \frac{1}{2.72 \times 10^3} = 3.68 \times 10^{-4} \text{ m s}^{-1}. \end{aligned}$$

This is the magnitude. The electron drift velocity is directed to the left, opposite to the rightward conventional-current arrow shown in the rod.

Step 3: (ii) Find the displacement from each charge Let P be the observation point at $(3, 4) \text{ m}$. The charge q_1 is at $(3, 0) \text{ m}$, while q_2 is at $(0, 4) \text{ m}$. Therefore

$$\begin{aligned} \vec{R}_1 &= \vec{r} - \vec{r}_1 = 4\hat{j} \text{ m}, & R_1 &= 4 \text{ m}, \\ \vec{R}_2 &= \vec{r} - \vec{r}_2 = 3\hat{i} \text{ m}, & R_2 &= 3 \text{ m}. \end{aligned}$$

Both charges are positive, so the field of q_1 points along $+\hat{j}$, and that of q_2 points along $+\hat{i}$. The charge-to-point distances, rather than the distance of P from the origin, must enter Coulomb's law.

Step 4: Calculate and add the perpendicular field components Substitute the charges in coulombs and use their respective distances:

$$\begin{aligned} \vec{E}_1 &= \frac{(9 \times 10^9)(16 \times 10^{-6})}{4^2} \hat{j} = 9.0 \times 10^3 \hat{j} \text{ N C}^{-1}, \\ \vec{E}_2 &= \frac{(9 \times 10^9)(1 \times 10^{-6})}{3^2} \hat{i} = 1.0 \times 10^3 \hat{i} \text{ N C}^{-1}. \end{aligned}$$

Superposition gives $\vec{E} = \vec{E}_1 + \vec{E}_2$. Because these components are perpendicular, their magnitudes cannot be added as scalars.

Step 5: Conclusion (i) $E_A : E_B = 2 : 1$, and the electron drift speed at B is $3.68 \times 10^{-4} \text{ m s}^{-1}$, directed to the left. (ii) The net electric field is

$$\vec{E} = (1.0 \times 10^3 \hat{i} + 9.0 \times 10^3 \hat{j}) \text{ N C}^{-1}.$$

Quick Tip to Solve: For the same material and current, both field and drift speed vary inversely with area. In the charge problem, subtract each charge's position from the observation point before assigning field components.