

CBSE Class 12 Physics Question Paper 2025 with Solution PDF-Set 55/5/3



Question Paper with Solutions

Conducted by the Central Board of Secondary Education (CBSE)

Time Allowed: 3 hours

Maximum Marks: 70

General Instructions

- (i) This question paper contains **33** questions. **All** questions are **compulsory**.
- (ii) 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. A beam of light of wavelength 720 nm in air enters water (refractive index = $\frac{4}{3}$). Its wavelength in water will be: [1 mark]

- (A) 540 nm
- (B) 480 nm
- (C) 420 nm
- (D) 720 nm

Correct Answer: (A) 540 nm

Solution:

Concept:

- Refraction changes the speed and wavelength of light, but its frequency f remains fixed by the source.
- For water of refractive index n relative to air, $v = c/n$. Since $\lambda = v/f$, the wavelength becomes $\lambda_w = \lambda_{\text{air}}/n$.

Step 1: Relate the wavelengths in the two media The same frequency occurs on both sides of the boundary. Thus the wavelength decreases in the same ratio as the speed:

$$\frac{\lambda_w}{\lambda_{\text{air}}} = \frac{v}{c} = \frac{1}{n}.$$

Step 2: Substitute the refractive index Using the given air wavelength and water's refractive index,

$$\lambda_w = \frac{720}{4/3} \text{ nm} = 720 \times \frac{3}{4} \text{ nm} = 540 \text{ nm}.$$

The values 480 nm and 420 nm do not satisfy the given ratio. The value 720 nm incorrectly assumes that wavelength, rather than frequency, remains unchanged.

Step 3: Conclusion The wavelength in water is 540 nm. Hence, the correct option is (A).

Quick Tip to Solve: Divide the air wavelength by the refractive index; in a denser optical medium the wavelength must decrease while the frequency stays fixed.

2. A capacitor of capacitance C has reactance X in an ac circuit. If the capacitance and the frequency of the applied voltage are doubled, the new reactance will become: [1 mark]

(A) $4X$

(B) $2X$

(C) $\frac{X}{2}$

(D) $\frac{X}{4}$

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

Solution:

Concept:

- Capacitive reactance is $X_C = 1/(2\pi fC)$, where f is the applied frequency and C is the capacitance.
- Reactance varies inversely with the product fC , so simultaneous changes in frequency and capacitance must both be included.

Step 1: Write the initial and final reactances Initially $X = 1/(2\pi fC)$. After the change, the frequency is $f' = 2f$ and the capacitance is $C' = 2C$, giving

$$X' = \frac{1}{2\pi(2f)(2C)}.$$

Step 2: Compare the denominator factors Each doubling contributes a factor of two to the denominator. Therefore,

$$\frac{X'}{X} = \frac{fC}{(2f)(2C)} = \frac{1}{4}.$$

Option (C) accounts for only one of the two changes. Options (A) and (B) predict an increase, contrary to the inverse dependence of capacitive reactance on both quantities.

Step 3: Conclusion The new capacitive reactance is $X/4$. Hence, the correct option is (D).

Quick Tip to Solve: Multiply the factors changing frequency and capacitance, then divide the original capacitive reactance by their product.

3. Four point charges Q each, are held at the four corners of a square of side l . The amount of work done in bringing a charge Q from infinity to the centre of the square will be: [1 mark]

- (A) $\frac{Q^2}{\pi\epsilon_0 l}$
(B) $\frac{\sqrt{2} Q^2}{\pi\epsilon_0 l}$
(C) $\frac{Q^2}{2\pi\epsilon_0 l}$
(D) Zero

Correct Answer: (B) $\frac{\sqrt{2} Q^2}{\pi\epsilon_0 l}$

Solution:

Concept:

- Electric potential is a scalar: the potential due to several fixed charges is the algebraic sum $V = \sum kQ_i/r_i$, where $k = 1/(4\pi\epsilon_0)$.
- With zero potential at infinity, the external work in bringing a charge Q slowly to potential V is $W = QV$.

Step 1: Find the centre-to-corner distance The diagonal of the square is $\sqrt{2}l$, so each corner is at distance $r = l/\sqrt{2}$ from its centre. All four equal charges contribute potentials of the same sign:

$$V = 4 \frac{kQ}{l/\sqrt{2}} = \frac{\sqrt{2} Q}{\pi\epsilon_0 l}.$$

Step 2: Calculate the work of bringing in the fifth charge The existing corner charges remain fixed, so only the interaction energy of the added charge changes:

$$W = QV = \frac{\sqrt{2} Q^2}{\pi\epsilon_0 l}.$$

The electric field cancels at the centre, but the scalar potentials do not; thus zero work is incorrect. Options (A) and (C) omit the correct centre-to-corner geometry and cannot equal the sum of all four contributions.

Step 3: Conclusion The required work is $\frac{\sqrt{2} Q^2}{\pi\epsilon_0 l}$. Hence, the correct option is (B).

Quick Tip to Solve: At a square's centre use half the diagonal, $l/\sqrt{2}$, and add potentials as scalars even when the net electric field is zero.

4. A metal sheet is inserted between the plates of a parallel plate capacitor of capacitance C . If the sheet partly occupies the space between the plates, the capacitance: [1 mark]

- (A) remains C
- (B) becomes greater than C
- (C) becomes less than C
- (D) becomes zero

Correct Answer: (B) becomes greater than C

Solution:

Concept:

- For an air-filled parallel plate capacitor, $C = \epsilon_0 A/d$, where A is the plate area and d is the separation, neglecting edge effects.
- The electric field inside a metal in electrostatic equilibrium is zero. An inserted metal slab therefore reduces the distance over which the potential difference is developed.

Step 1: Account for the field-free metal thickness Consider an inserted metal sheet of thickness t , with $0 < t < d$, which does not bridge the plates. For the region it occupies, the total air-gap thickness becomes $d - t$. If it covers the full area, its capacitance is

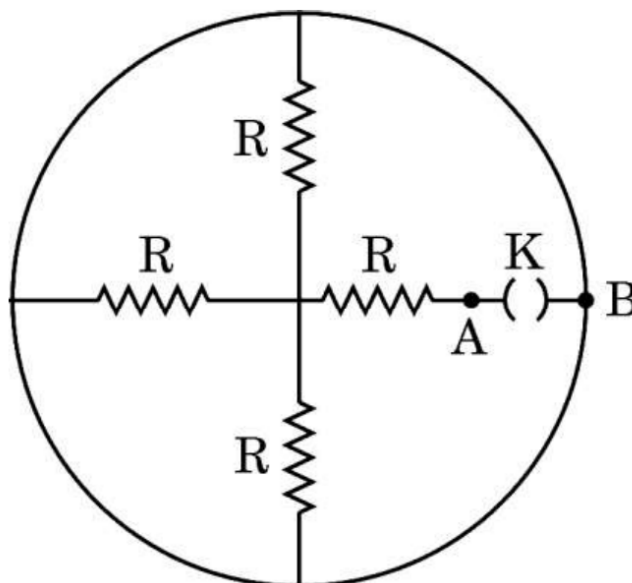
$$C' = \frac{\epsilon_0 A}{d - t}.$$

Step 2: Compare the capacitances Since $d - t < d$, the ratio is $C'/C = d/(d - t) > 1$. If the sheet covers only part of the plate area, that covered region has an increased capacitance and is in parallel with the unchanged region, so the total still increases. Remaining equal to C , decreasing, or becoming zero would contradict this reduced effective gap.

Step 3: Conclusion The capacitance becomes greater than C . Hence, the correct option is (B).

Quick Tip to Solve: For a metal sheet between capacitor plates, subtract its thickness from the field-carrying gap; a smaller effective gap gives a larger capacitance.

5. 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:

- Ideal connecting wires form a single equipotential node. Resistors connected between the same two nodes are in parallel.
- Series resistances add, while parallel resistances satisfy $1/R_p = \sum_i 1/R_i$.

Step 1: Identify the paths when the key is open The entire outer circular wire belongs to node B . The top, bottom and left resistors each connect the centre junction to this same outer node, so these three resistors are in parallel. The right-hand resistor connects terminal A to the centre. Opening K removes the direct wire connection from A to B , but leaves the path through these resistors intact.

Step 2: Reduce the parallel group and its series resistor For the three equal resistors,

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

The right-hand resistor is in series with this group, giving

$$R_{AB} = R + \frac{R}{3} = \frac{4R}{3}.$$

The value $4R$ assumes all four are in series, and $R/4$ assumes all four share both nodes. Infinite resistance would require every path between A and B to be broken, which is not the case.

Step 3: Conclusion The equivalent resistance with the key open is $4R/3$. Hence, the correct option is (D).

Quick Tip to Solve: First collapse the outer circular wire into one node; the three spokes to that node are parallel, with the fourth resistor in series.

6. 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:

- A particle of mass m and charge magnitude $|q|$, accelerated from rest through potential difference V , gains kinetic energy $|q|V = mv^2/2$.
- For velocity perpendicular to a uniform magnetic field B , magnetic force supplies the centripetal force: $|q|vB = mv^2/r$, giving $r = mv/(|q|B)$.

Step 1: Eliminate the unknown charge-to-mass ratio Rearranging the energy equation gives $m/|q| = 2V/v^2$. Substitute this into the magnetic-radius formula:

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

Thus neither the particle's mass nor its charge needs to be known separately.

Step 2: Substitute in SI units and compare the options Use $V = 10 \text{ kV} = 10^4 \text{ V}$, $v = 10^6 \text{ m s}^{-1}$ and $B = 0.4 \text{ T}$:

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

The value 2.5 cm misses the factor of two from kinetic energy. Neither 8 cm nor 10 cm satisfies the combined energy and magnetic-force equations for the printed values.

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

Quick Tip to Solve: When accelerating voltage and final speed are both given, combine the two laws first to use $r = 2V/(vB)$, avoiding unknown particle parameters.

7. 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 magnetic dipole moment of a single current loop has magnitude $\mu = IA$, where I is the current and A is the area enclosed by the loop.
- For a circular loop of radius r , $A = \pi r^2$. With current in amperes and radius in metres, the moment is in A m^2 .

Step 1: Convert the radius and write the area The given radius is $r = 14 \text{ cm} = 0.14 \text{ m}$. Therefore,

$$A = \pi(0.14)^2 \text{ m}^2 = 0.0196\pi \text{ m}^2.$$

Radius must be converted to metres before squaring to obtain the area in SI units.

Step 2: Multiply the current by the loop area Substituting $I = 10/\pi \text{ A}$, the factors of π cancel:

$$\mu = \frac{10}{\pi} \times 0.0196\pi \text{ A m}^2 = 0.196 \text{ A m}^2.$$

Option (A) loses approximately a factor of ten. Option (B) uses the numerical radius without the required area calculation, while option (D) retains an extra factor of π . None equals the product IA .

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

Quick Tip to Solve: Cancel the π in the given current against the circular area first, then square the radius expressed in metres.

8. 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 strongly associated with the heating effect of electromagnetic waves and with thermal radiation from bodies.
- Earth's temperature is maintained by the balance between absorbed solar energy and emitted

radiation; atmospheric absorption and re-emission of infrared radiation contribute to its warmth.

Step 1: Identify the relevant radiation Infrared rays from the Sun are absorbed by matter and transfer energy to molecular motion. They are conventionally called heat rays and are the band associated with maintaining the Earth's warmth in this question.

Step 2: Compare the other choices Visible light also supplies solar energy, but infrared is the characteristic thermal-radiation answer. Ultraviolet rays are associated mainly with photochemical effects, and gamma rays are highly penetrating ionising radiation; neither is the usual band responsible for this heating role.

Step 3: Conclusion Infrared rays play the stated role. Hence, the correct option is (A).

Quick Tip to Solve: Associate the phrase "maintaining Earth's warmth" with infrared heat radiation, while UV is associated with chemical effects.

9. 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 speed of an electromagnetic wave in a medium is $v = 1/\sqrt{\mu\epsilon}$, where μ is permeability and ϵ is permittivity.
- Speed has dimensions $[v] = [LT^{-1}]$; powers of a physical quantity multiply its dimensional exponents by the same power.

Step 1: Relate the printed expression to speed The question asks for the inverse product, rather than the product itself. Squaring the wave-speed relation gives

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

Step 2: Square the dimensional formula Therefore,

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

Option (A) is the dimension of speed rather than speed squared. Option (C) includes an extra mass factor and has the dimensions of energy. Option (D) also contains mass and has incorrect length and time powers.

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

Quick Tip to Solve: Replace $(\mu\epsilon)^{-1}$ by v^2 first; overlooking the inverse reverses both length and time powers.

10. 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 energy $E = h\nu$ and momentum $p = E/c = h\nu/c = h/\lambda$, where h is Planck's constant and λ is its vacuum wavelength.
- Photon momentum increases with frequency and decreases with wavelength; it does not depend on the number of photons in a beam.

Step 1: Compare wavelengths in the spectrum X-rays have much shorter wavelengths than microwaves, TV waves and AM radio waves. Equivalently, their frequencies are much higher than those of the other three listed bands.

Step 2: Apply the momentum relation Since $p = h/\lambda$, the smallest wavelength gives the largest momentum per photon. AM radio waves and TV waves belong to radio-frequency bands, while microwaves also have far longer wavelengths than X-rays. Thus none of options (B), (C) or (D) can give the largest photon momentum among these choices.

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

Quick Tip to Solve: For the largest photon momentum, select the shortest wavelength in the list; beam intensity is irrelevant to momentum per photon.

11. 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 a non-relativistic particle of mass m and kinetic energy K , momentum is $p = \sqrt{2mK}$, so its de Broglie wavelength is $\lambda = h/\sqrt{2mK}$.
- An alpha particle has approximately four times the mass of a proton: $m_\alpha = 4m_p$. The question also gives $K_\alpha = 4K_p$.

Step 1: Form the wavelength ratio Planck's constant and the factor 2 cancel in the ratio. Since wavelength is inversely proportional to the square root of mass times kinetic energy,

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

Step 2: Substitute both factors of four Using both the mass ratio and the energy ratio gives

$$\frac{\lambda_\alpha}{\lambda_p} = \sqrt{\frac{1}{4 \times 4}} = \sqrt{\frac{1}{16}} = \frac{1}{4}.$$

Option (A) misses the square root, while (D) accounts for only one factor of four. Option (B) does not follow from the square-root dependence either.

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 and kinetic-energy ratios before taking the square root, then invert to obtain the wavelength ratio.

12. 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:

- For coherent waves of amplitudes a_1 and a_2 , the resultant intensity is proportional to $a_1^2 + a_2^2 + 2a_1a_2 \cos \phi$, where ϕ is their phase difference.
- In the relative intensity units used in the options, the common proportionality factor is taken as unity; intensity is the square of resultant amplitude.

Step 1: Use the equal amplitudes Substituting $a_1 = a_2 = a$ in the interference relation gives

$$I = 2a^2(1 + \cos \phi) = 4a^2 \cos^2(\phi/2).$$

The phase difference varies across the screen and produces alternate bright and dark fringes.

Step 2: Evaluate the two extremes At destructive interference, $\phi = \pi$ and the amplitudes cancel, giving $I_{\min} = 0$. At constructive interference, $\phi = 0$ and the amplitude becomes $2a$, giving $I_{\max} = 4a^2$. The value $2a^2$ is the sum of individual intensities, not the coherent maximum. Options (C) and (D) incorrectly exclude complete cancellation.

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

Quick Tip to Solve: For equal coherent amplitudes, use $(a - a)^2$ and $(a + a)^2$ to obtain the minimum and maximum directly.

13. 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:

- Nuclear binding energy is $B = \Delta mc^2$, where Δm is the difference between the total mass of separated nucleons and the mass of their bound nucleus.
- Binding energy per nucleon, B/A , measures average binding, where A is mass number. Its variation with A is not a continuous increase over all nuclei.

Step 1: Judge the assertion When nucleons form a bound nucleus, energy is released and the final rest mass is smaller than the sum of the free-nucleon masses. This mass defect corresponds to the binding energy through $B = \Delta mc^2$. Assertion (A) is true.

Step 2: Judge the reason Binding energy per nucleon generally rises for light nuclei, reaches its maximum near the iron-nickel region, and then slowly decreases towards heavy nuclei. Therefore it does not increase with mass number for all nuclei. Reason (R) is false.

Step 3: Check the explanatory link The assertion follows from mass-energy equivalence, not from a universal increase of binding energy per nucleon. Since R is false, it cannot explain A. Both statements cannot be true as required by options (A) and (B), and option (D) incorrectly rejects the true assertion.

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

Quick Tip to Solve: Test the phrase "for all nuclei" against the fall of binding energy per nucleon beyond the iron-nickel maximum.

14. 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 due to electrostatic repulsion between a positive alpha particle and the compact, positively charged atomic nucleus.
- Typical nuclear and atomic sizes are of order 10^{-15} m and 10^{-10} m, respectively; their ratio is approximately 10^{-5} .

Step 1: Judge the assertion A scattering angle of π means backward scattering through 180° . The observation that a very small fraction of alpha particles returned backwards showed that strong repulsion could arise in a tiny region containing concentrated positive charge and most of the atomic mass. It supported the discovery of the nucleus, so Assertion (A) is true.

Step 2: Judge the reason The nucleus is extremely small compared with the atom:

$$\frac{\text{nuclear size}}{\text{atomic size}} \simeq \frac{10^{-15}}{10^{-10}} = 10^{-5}.$$

Only a few incident particles approach this compact charge concentration nearly head-on and suffer backward deflection; most travel through the largely empty atom. Reason (R) is true.

Step 3: Check the explanatory link The tiny extent of the nucleus accounts for the rarity of encounters that cause backward scattering. Thus the reason explains the observation stated in the assertion. Option (B) misses this connection, while (C) and (D) wrongly declare one or both statements false.

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

Quick Tip to Solve: Separate the two clues: rare backward scattering indicates a tiny nucleus, while strong backward deflection indicates concentrated positive charge.

15. 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:

- Silicon is tetravalent. A trivalent dopant leaves one bond short of an electron and acts as an acceptor, producing a hole.
- In an ordinary p-type semiconductor with ionised acceptors and negligible minority electrons, the hole density is $p \simeq N_A$, where N_A is the acceptor density.

Step 1: Judge the assertion The assertion is true. P-type silicon is formed using trivalent impurities such as boron. Pentavalent impurities provide an extra electron and behave as donors, producing n-type silicon instead.

Step 2: Judge the reason The reason is also true in the usual extrinsic regime: each ionised acceptor creates approximately one mobile hole in the valence band, so $p \simeq N_A$.

Step 3: Test the explanatory connection The reason describes the relation between the concentrations of holes and acceptors. It does not explain why pentavalent atoms are unsuitable for producing p-type material; that requires comparing their five valence electrons with silicon's four. Thus the two statements are true, but the stated reason is not the explanation of the assertion. Options (C) and (D) wrongly deny a true statement, while (A) wrongly asserts this explanatory link.

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

Quick Tip to Solve: Separate dopant valency from carrier concentration: three valence electrons create holes; five provide donor electrons.

16. 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 its final energy level: Balmer transitions terminate at $n_f = 2$, whereas Lyman transitions terminate at $n_f = 1$.
- For emission between allowed Bohr energy levels, the photon energy is $h\nu = E_i - E_f$. The initial and final principal quantum numbers need not be consecutive.

Step 1: Judge the assertion The assertion is false. The ground state is $n = 1$, and transitions to it form the Lyman series. The Balmer series is formed by transitions from $n_i = 3, 4, 5, \dots$ to the first excited state, $n_f = 2$.

Step 2: Judge the reason The reason is false. Bohr's model does not restrict jumps to successive orbits. For example, the $n = 4$ to $n = 2$ transition skips an intermediate orbit and is a Balmer-series transition.

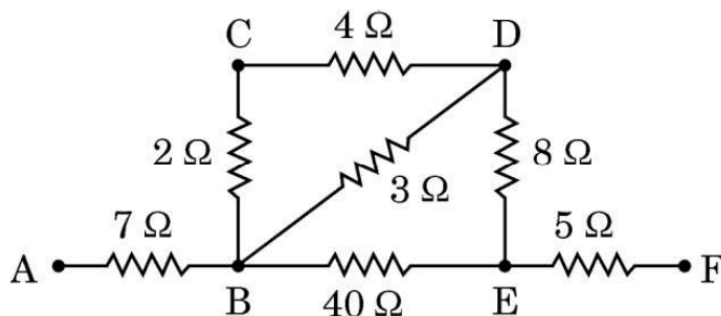
Step 3: Check the reason against the assertion Since both statements are false, the reason cannot explain the assertion. Options (A) and (B) require both statements to be true, and option (C) requires the assertion to be true, so all three are excluded.

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 the final orbit: Lyman ends at 1 and Balmer at 2, regardless of how many orbits are skipped.

Section B (10 marks)

17. Find the effective resistance of the network of resistors between points A and F as shown in the figure. [2 marks]



Solution:

Concept:

- Series resistors carry the same current and have equivalent resistance $R_s = R_1 + R_2$. Their common junction must have no other current path.
- Parallel resistors share the same two end nodes and have equivalent resistance $R_p = R_1 R_2 / (R_1 + R_2)$.

Step 1: Reduce the triangular section between B and D The 2Ω resistor BC and the 4Ω resistor CD are in series, since C has no other branch. Their 6Ω equivalent is in parallel with the direct 3Ω resistor BD:

$$R_{BD} = \frac{(2 + 4) \times 3}{(2 + 4) + 3} = 2\Omega.$$

Step 2: Reduce the network between B and E After replacing the BCD triangle, the 2Ω equivalent is in series with the 8Ω resistor DE. This gives a 10Ω path from B to E, in parallel with the direct 40Ω branch:

$$R_{BE} = \frac{10 \times 40}{10 + 40} = 8\Omega.$$

Step 3: Include the two outer resistors All current entering at A passes through the 7Ω resistor AB before splitting at B. After recombining at E it passes through the 5Ω resistor EF. These outer resistors are therefore in series with the reduced network:

$$R_{AF} = 7 + R_{BE} + 5 = 7 + 8 + 5 = 20\Omega.$$

Step 4: Conclusion The effective resistance between A and F is 20Ω .

Quick Tip to Solve: Begin at the unbranched node C: combine 2 and 4 in series before using the diagonal 3-ohm branch in parallel.

18. A current of 5 A is passing along +X direction through a wire lying along X-axis. Find the magnetic field $\vec{B}$ at a point $\vec{r} = (3\hat{i} + 4\hat{j})$ m due to 1 cm element of the wire, centered at origin.

[2 marks]

Solution:

Concept:

- Biot–Savart law gives the field of a short current element: $\Delta\vec{B} = \frac{\mu_0}{4\pi} \frac{I \Delta\vec{\ell} \times \vec{r}}{r^3}$, where $\vec{r}$ points from the element to the field point.
- The cross product sets the field direction. In a right-handed Cartesian system, $\hat{i} \times \hat{j} = \hat{k}$, and $\mu_0/(4\pi) = 10^{-7} \text{ T m A}^{-1}$.

Step 1: Write the length and position vectors The current flows along positive X, so the length vector points along $\hat{i}$. Convert centimetres to metres before substitution:

$$\Delta\vec{\ell} = 10^{-2}\hat{i} \text{ m}, \quad \vec{r} = (3\hat{i} + 4\hat{j}) \text{ m}, \quad r = \sqrt{3^2 + 4^2} = 5 \text{ m}.$$

The element length is much smaller than its distance from the observation point, so the short-element form of Biot–Savart law applies.

Step 2: Evaluate the cross product and field Only the Y component of $\vec{r}$ contributes, since $\hat{i} \times \hat{i} = 0$:

$$\Delta\vec{\ell} \times \vec{r} = 10^{-2}\hat{i} \times (3\hat{i} + 4\hat{j}) = 4 \times 10^{-2}\hat{k} \text{ m}^2.$$

Therefore,

$$\Delta\vec{B} = 10^{-7} \frac{5(4 \times 10^{-2})}{5^3} \hat{k} = 1.6 \times 10^{-10} \hat{k} \text{ T}.$$

Step 3: Conclusion The magnetic field due to the specified element is $\vec{B} = 1.6 \times 10^{-10} \hat{k} \text{ T}$, directed along the positive Z-axis.

Quick Tip to Solve: Use the full distance 5 m and the perpendicular component 4 m in the cross product; do not substitute 4 m for the distance.

19. Define the term, ‘distance of closest approach’. A proton of 3.95 MeV energy approaches a target nucleus $Z = 79$ in head-on position. Calculate its distance of closest approach.

[2 marks]

Solution:

Concept:

- For a head-on approach to a heavy positive nucleus, electrostatic repulsion slows the incident proton until its kinetic energy is momentarily zero at the turning point.
- Taking potential energy as zero at infinity, energy conservation gives $K = \frac{kZe^2}{r_{\min}}$, where $k = 1/(4\pi\epsilon_0)$, Ze is the target charge and e is the proton charge.

Step 1: Define the distance of closest approach The distance of closest approach is the minimum separation between the centres of an incident charged particle and the target nucleus during a head-on encounter. At this point the particle momentarily comes to rest before returning, its initial kinetic energy having been converted into electrostatic potential energy. We use the standard heavy, stationary target approximation.

Step 2: Convert the proton energy and apply conservation The projectile is a proton of charge $+e$, and the target has charge $+79e$. Its initial energy in SI units is

$$K = 3.95 \times 10^6 \times 1.6 \times 10^{-19} = 6.32 \times 10^{-13} \text{ J.}$$

Using $k = 9 \times 10^9 \text{ N m}^2\text{C}^{-2}$,

$$r_{\min} = \frac{kZe^2}{K} = \frac{(9 \times 10^9)(79)(1.6 \times 10^{-19})^2}{6.32 \times 10^{-13}} = 2.88 \times 10^{-14} \text{ m.}$$

Step 3: Conclusion The proton's distance of closest approach is $2.88 \times 10^{-14} \text{ m}$, or 28.8 fm.

Quick Tip to Solve: Use projectile charge e for a proton, not $2e$ as for an alpha particle, and convert MeV to joules before using SI constants.

20(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:

- Refraction at a spherical surface obeys $n_2/v - n_1/u = (n_2 - n_1)/R$, where u and v are signed object and image distances from its pole.
- In the Cartesian convention, distances measured along the incident light are positive. A negative image distance denotes a virtual image on the incident side.

Step 1: Assign the signed distances Take incident light to travel from the object in air towards the medium. The object is in front of the surface, so $u = -R/3$. The convex surface has its centre of curvature inside the refracting medium, so its signed radius is $+R$. The incident and refracted refractive indices are $n_1 = 1$ and $n_2 = n$, respectively.

Step 2: Apply the spherical refraction formula Substitution gives

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

Because the given refractive index is positive and less than four, the right-hand side is negative. The refracted rays therefore diverge, and their backward extensions meet on the air side of the surface.

Step 3: Conclusion The image is **virtual**, at $v = nR/(n-4) = -nR/(4-n)$. It lies a distance $nR/(4-n)$ in front of the surface, on the same side as the object.

Quick Tip to Solve: For a convex refracting surface, use a positive radius but a negative real-object distance; inspect the sign of the resulting image distance.

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

Solution:

Concept:

- A path difference Δ produces phase difference $\phi = 2\pi\Delta/\lambda$, where λ is the wavelength.
- In the usual equal-intensity double slit arrangement, resultant intensity is $I_P = 4I_s \cos^2(\phi/2)$, with I_s the intensity from either slit alone. Thus the central maximum is $I = 4I_s$.

Step 1: Convert the path difference into phase At the central maximum the waves arrive in phase. At the specified point, the additional path is one-third of a wavelength, so the phase difference is one-third of a full cycle:

$$\phi = \frac{2\pi}{\lambda} \left(\frac{\lambda}{3} \right) = \frac{2\pi}{3}.$$

The intensity formula involves half this phase difference, namely $\phi/2 = \pi/3$.

Step 2: Express the intensity relative to the maximum Divide the interference intensity by its central-maximum value, eliminating the unknown single-slit intensity:

$$\frac{I_P}{I} = \cos^2 \left(\frac{\phi}{2} \right) = \cos^2 \left(\frac{\pi}{3} \right) = \left(\frac{1}{2} \right)^2 = \frac{1}{4}.$$

The waves partly cancel at this point, but the path difference is not an odd half-wavelength, so the intensity is nonzero.

Step 3: Conclusion The intensity at the given point is $I_P = I/4$, one-quarter of the central-maximum intensity.

Quick Tip to Solve: When central intensity is given, use the ratio $I_P/I = \cos^2(\pi\Delta/\lambda)$; square the cosine, not the path difference.

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 h is Planck's constant, ν is the incident frequency, and ν_0 is the threshold frequency.
- The cut-off or stopping potential magnitude V_0 satisfies $eV_0 = K_{\max}$, where e is the positive magnitude of electron charge.

Step 1: Find the frequency above threshold Only photon energy exceeding the work function appears as maximum photoelectron kinetic energy. The required frequency difference is

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

Since this is positive, the incident radiation can eject photoelectrons from the metal.

Step 2: Equate the stopping work to the kinetic energy Using $h = 6.63 \times 10^{-34} \text{ J s}$ and $e = 1.6 \times 10^{-19} \text{ C}$,

$$\begin{aligned}K_{\max} &= (6.63 \times 10^{-34})(3.2 \times 10^{14}) \\&= 2.1216 \times 10^{-19} \text{ J}, \\V_0 &= \frac{2.1216 \times 10^{-19}}{1.6 \times 10^{-19}} \\&= 1.326 \text{ V}.\end{aligned}$$

This retarding potential removes even the largest kinetic energy, reducing the photocurrent to zero.

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

Quick Tip to Solve: Subtract the threshold frequency before multiplying by h/e ; the full photon energy is not available as electron kinetic energy.

Section C (21 marks)

22. (a) “There is a limit to the amount of charge that can be stored on a given capacitor.” Explain.
(b) A capacitor is charged by a battery to a potential difference V . It is disconnected from the battery and connected across another identical uncharged capacitor. Calculate the ratio of total energy stored in the combination to the initial energy stored in the capacitor. [3 marks]

Solution:

Concept:

- A capacitor stores charge $Q = CV$, where C is its capacitance and V the potential difference. Its dielectric can withstand only a finite electric field before electrical breakdown.
- The energy stored in a capacitor is $U = \frac{1}{2}CV^2$. On connecting isolated capacitors in parallel, charge is conserved and their final potential differences become equal.

Step 1: Explain the charge limit in part (a) For a given capacitor, increasing the stored charge increases its potential difference and the electric field between its plates. Beyond the dielectric strength of the insulating material, the dielectric breaks down and conducts. Charge then leaks or discharges between the plates, so it cannot be stored reliably above this limit. If V_{bd} denotes the breakdown voltage, the limiting charge is $Q_{\max} = CV_{\text{bd}}$; a practical capacitor is operated below this value. For parallel plates separated by d , $V_{\text{bd}} = E_{\text{bd}}d$.

Step 2: Determine the common potential in part (b) Let each identical capacitor have capacitance C . Initially the first capacitor carries charge CV and the other is uncharged. Because the battery is disconnected, it supplies no extra charge during redistribution. The parallel combination has capacitance $2C$, so conservation of charge gives

$$CV = (2C)V_f \Rightarrow V_f = \frac{V}{2}.$$

Each capacitor therefore finally carries charge $CV/2$.

Step 3: Compare total final energy with initial energy The initial energy belongs to the charged

capacitor alone, whereas both capacitors store energy after connection:

$$U_i = \frac{1}{2}CV^2,$$
$$U_f = 2 \left[\frac{1}{2}C \left(\frac{V}{2} \right)^2 \right] = \frac{1}{4}CV^2,$$
$$\frac{U_f}{U_i} = \frac{CV^2/4}{CV^2/2} = \frac{1}{2}.$$

Electrostatic energy is not conserved during redistribution: the decrease is released mainly as heat in the connecting circuit, with possible electromagnetic radiation during the transient.

Step 4: Conclusion (a) Dielectric breakdown sets the maximum charge that a given capacitor can store. (b) The ratio of the final total stored energy to the initial stored energy is $\boxed{1 : 2}$.

Quick Tip to Solve: After the battery is removed, conserve charge first. For two identical capacitors the common voltage halves, and the final energy must include both capacitors.

23. (a) “You cannot see a person standing on the other side of a boundary wall but can hear him.” Explain with reason.

(b) Light of wavelength 750 nm is incident normally on a slit of width 1.5 mm. Diffraction pattern is obtained on a screen 1.0 m away from the slit. Find the distance of the nearest point from the central maxima at which the intensity is zero. [3 marks]

Solution:

Concept:

- Diffraction is the spreading of a wave around the edges of an obstacle. It is appreciable when the wavelength is comparable to the relevant obstacle or aperture size.
- For a single slit of width a , dark fringes satisfy $a \sin \theta = n\lambda$, where λ is the wavelength and $n = 1, 2, \dots$. The nearest minimum has $n = 1$.
- At small angles, the transverse distance on a screen a distance D away is $y = D \tan \theta \simeq D \sin \theta$.

Step 1: (a) Compare the wavelengths of sound and light Sound has a much longer wavelength than visible light. Sound therefore diffracts appreciably around the top and sides of the boundary wall and reaches a listener in its geometrical shadow. Visible light has an extremely small wavelength compared with the wall, so its diffraction into that shadow is negligible. The wall blocks the direct light needed to see the person, while sound can still reach the listener.

Step 2: (b) Identify the first diffraction minimum Convert the data into SI units:

$$\lambda = 750 \times 10^{-9} \text{ m}, \quad a = 1.5 \times 10^{-3} \text{ m}, \quad D = 1.0 \text{ m}.$$

The central maximum lies at $\theta = 0$. Its nearest zero-intensity points occur when the path difference across the slit equals one wavelength:

$$\sin \theta_1 = \frac{\lambda}{a} = 5.0 \times 10^{-4}.$$

This small value justifies the small-angle approximation.

Step 3: Calculate the distance from the centre Using the first-minimum condition and the screen

geometry,

$$y_1 \simeq \frac{D\lambda}{a} = \frac{1.0(750 \times 10^{-9})}{1.5 \times 10^{-3}} = 5.0 \times 10^{-4} \text{ m.}$$

There is one such point on each side of the central maximum. The question asks for the distance to either nearest point, rather than the full distance between the two minima.

Step 4: Conclusion (a) Sound bends appreciably around the wall by diffraction, whereas visible light does not. (b) The nearest zero-intensity point is 0.50 mm from the centre on either side.

Quick Tip to Solve: For the nearest dark point use $D\lambda/a$; double it only when asked for the full width of the central maximum.

24. The magnetic moment (5 J/T) of a bar magnet points along a uniform magnetic field 0.4 T .

(a) Calculate (i) the potential energy of the bar magnet, and (ii) the work done in turning the magnet by 180° .

(b) In which case is the potential energy of the magnet minimum?

[3 marks]

Solution:

Concept:

- The potential energy of a magnetic dipole is $U = -\vec{m} \cdot \vec{B} = -mB \cos \theta$, where m is its magnetic moment, B the uniform field and θ the angle between them. The conventional zero is at $\theta = 90^\circ$.
- In a slow rotation with no change in kinetic energy, the work done by an external agent equals the change in potential energy: $W_{\text{ext}} = U_f - U_i$. The magnetic field does the opposite work.
- The stable orientation of a dipole has the least potential energy; it occurs when the magnetic moment is parallel to the field.

Step 1: (a)(i) Evaluate the initial potential energy The magnetic moment points along the field, so the initial angle is $\theta_i = 0^\circ$. With $m = 5 \text{ J T}^{-1}$ and $B = 0.4 \text{ T}$,

$$mB = (5)(0.4) = 2 \text{ J}, \quad U_i = -mB \cos 0^\circ = -2 \text{ J.}$$

The negative sign follows from the chosen energy reference and indicates that the aligned dipole has lower energy than the perpendicular orientation.

Step 2: (a)(ii) Find the work needed for the half-turn Turning the magnet through 180° makes its magnetic moment antiparallel to the field. Thus,

$$U_f = -mB \cos 180^\circ = +2 \text{ J.}$$

The external agent must supply the increase in energy:

$$W_{\text{ext}} = U_f - U_i = (+2) - (-2) = 4 \text{ J.}$$

This is positive because the rotation is against the field's aligning tendency. Equivalently, the work done by the magnetic field in the same rotation is -4 J .

Step 3: (b) Determine the minimum-energy orientation In $U = -mB \cos \theta$, the product mB is positive. Therefore U is smallest when $\cos \theta$ is largest, namely $\cos \theta = 1$. This occurs at $\theta = 0^\circ$, when the magnetic moment is parallel to the field. A small displacement from this orientation produces a restoring torque, so it is stable equilibrium.

Step 4: Conclusion (a)(i) $U = -2\text{ J}$. (a)(ii) The required external work is 4 J . (b) Potential energy is minimum when the magnetic moment is parallel to the field; its minimum value here is -2 J .

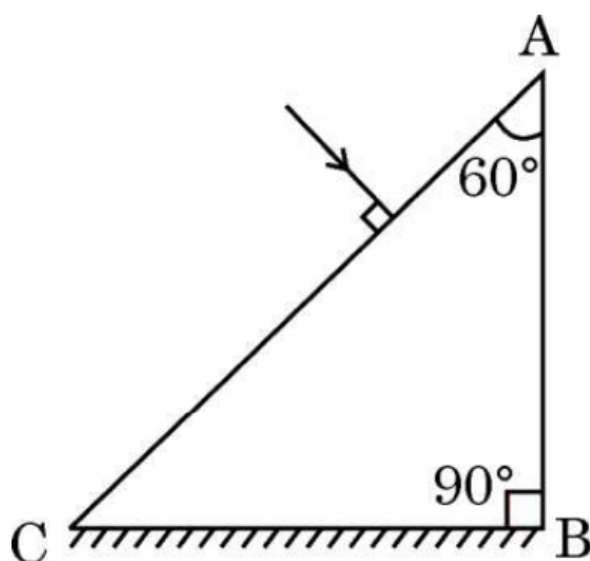
Quick Tip to Solve: For a rotation from parallel to antiparallel, energy changes from $-mB$ to $+mB$, so the required work is $2mB$.

25. A right-angled prism ABC (refractive index $\sqrt{2}$) is kept on a plane mirror as shown in the figure. A ray of light is incident normally on the face AC .

(a) Trace the path of the ray as it passes through the prism.

(b) Find the angle of deviation produced by the prism.

[3 marks]



Solution:

Concept:

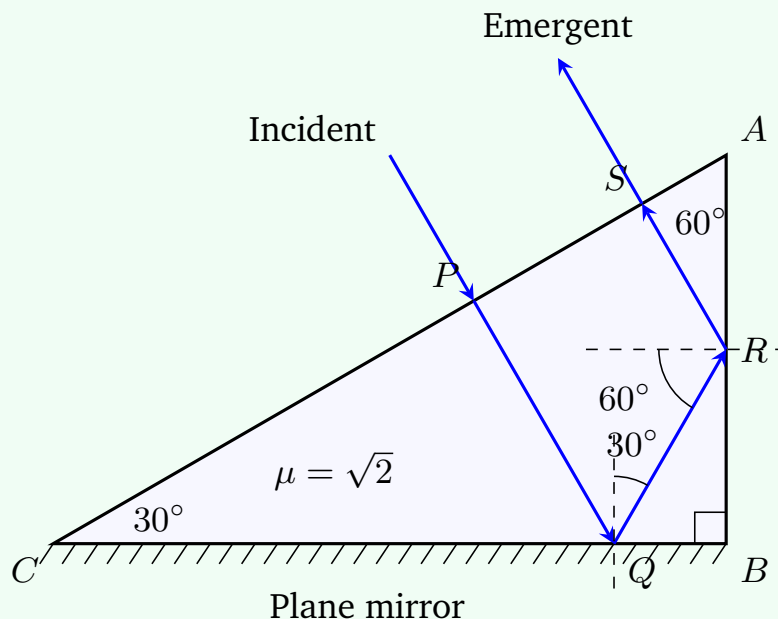
- A ray incident normally on a refracting surface travels undeviated. At a plane mirror, the angles of incidence and reflection are equal, measured from the normal.
- For a prism of refractive index μ in air, the critical angle c satisfies $\sin c = 1/\mu$. Total internal reflection occurs when the internal incidence angle exceeds c .
- Net deviation compares the original incident direction with the final emergent direction. Here $\angle A = 60^\circ$, $\angle B = 90^\circ$ and $\angle C = 30^\circ$.

Step 1: (a) Trace entry and reflection at the mirror The ray enters the upper portion of face AC , as shown in the question, at P . Normal incidence means that it enters without bending. Since AC is inclined at 30° to the base BC , the ray travels downward and rightward at 60° to the horizontal. It reaches the mirror at Q , making 30° with the vertical normal. The reflected ray travels upward and rightward at 60° to the horizontal and reaches face AB at R . The mirror is in contact with the base; its reflection is represented at Q .

Step 2: Test reflection at the vertical face The normal to vertical face AB is horizontal. Therefore the internal incidence angle at R is 60° . For the prism–air boundary,

$$c = \sin^{-1}\left(\frac{1}{\sqrt{2}}\right) = 45^\circ.$$

Since $i_R = 60^\circ > 45^\circ$, total internal reflection occurs at AB . The ray now travels upward and leftward, at 120° measured anticlockwise from the rightward horizontal. This direction is perpendicular to AC , whose inclination is 30° . It therefore reaches AC normally at S and emerges without bending.



Ray path $P \rightarrow Q \rightarrow R \rightarrow S$: mirror reflection at Q , total internal reflection at R .

Step 3: (b) Compare the incident and emergent directions The original incident direction was -60° relative to the rightward horizontal; the final emergent direction is 120° . Thus,

$$\delta = 120^\circ - (-60^\circ) = 180^\circ.$$

The two rays are parallel but oppositely directed. Equivalently, the mirror changes the direction by $180^\circ - 2(30^\circ) = 120^\circ$, and total internal reflection changes it by $180^\circ - 2(60^\circ) = 60^\circ$ in the same sense.

Step 4: Conclusion (a) The ray enters AC normally, reflects at the mirror on BC , undergoes total internal reflection at AB , and emerges normally through AC . (b) The net deviation is 180° .

Quick Tip to Solve: At vertical face AB , use the horizontal normal: $i = 60^\circ > c = 45^\circ$. The final ray is antiparallel to the incident ray.

26(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:

- The charge on a conducting sphere of radius r and surface charge density σ_s is $Q = 4\pi r^2 \sigma_s$.
- Far-separated spheres have potentials $V = Q/(4\pi\epsilon_0 r)$. Connecting them by a wire equalises their potentials while conserving their total charge.

Step 1: Calculate the initial total charge The stated densities are surface charge densities because excess charge on a metal ball resides on its surface. Thus the radii R and $2R$ must be used in their

respective surface areas:

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

Step 2: Apply equal potential after connection Let the final charges be Q'_A and Q'_B . The balls are far apart, so mutual influence on their potentials is negligible. In the usual idealisation, the thin connecting wire carries negligible charge. At electrostatic equilibrium,

$$\frac{Q'_A}{4\pi\epsilon_0 R} = \frac{Q'_B}{4\pi\epsilon_0(2R)} \Rightarrow Q'_B = 2Q'_A.$$

Conservation of charge now gives

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

Step 3: Convert the final charges to surface densities Divide each charge by the surface area of the ball on which it resides:

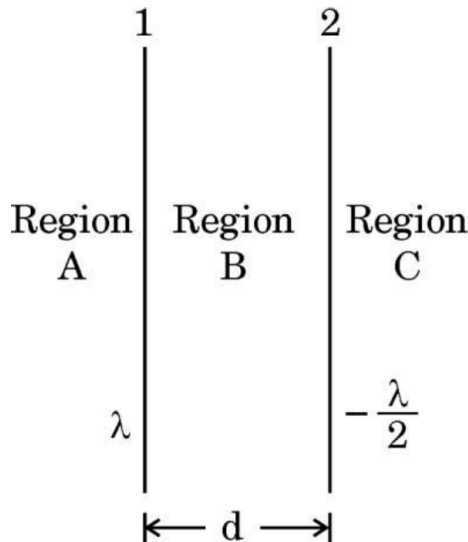
$$\sigma'_A = \frac{Q'_A}{4\pi R^2} = \frac{14\sigma}{3}, \quad \sigma'_B = \frac{Q'_B}{16\pi R^2} = \frac{7\sigma}{3}.$$

The smaller ball has the larger final surface density, even though the larger ball carries twice its charge. Equal potential does not mean equal charge or equal surface density.

Step 4: Conclusion The final charge densities are $\sigma'_A = 14\sigma/3$ and $\sigma'_B = 7\sigma/3$.

Quick Tip to Solve: For connected far-separated spheres, first use $Q'_A/Q'_B = R_A/R_B$; then divide by areas to get $\sigma'_A/\sigma'_B = R_B/R_A$.

26(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 field at perpendicular distance r from an infinite wire of linear charge density λ_i has magnitude $E = |\lambda_i|/(2\pi\epsilon_0 r)$.
- The field points away from a positive wire and towards a negative wire. Zero net field requires equal magnitudes and opposite directions.

Step 1: Check the field directions in each region Take wire 1 at $x = 0$ and wire 2 at $x = d$, with $\lambda > 0$. Region A is to the left of both wires, region B lies between them, and region C is to their right. 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. Cancellation is therefore impossible between the wires.

Step 2: Exclude region A At a point a distance $a > 0$ to the left of wire 1, the distances from wires 1 and 2 are a and $a + d$. The fields oppose, but their magnitude ratio is

$$\frac{E_1}{E_2} = \frac{\lambda/a}{(\lambda/2)/(a+d)} = \frac{2(a+d)}{a} > 2.$$

The more highly charged wire is also nearer, so its field always dominates in region A. There is no finite cancellation point there.

Step 3: Equate the opposing fields in region C Let the required distance from wire 1 be $x > d$. Its distance from wire 2 is then $x - d$. Here E_1 points right and E_2 points left. Equating their magnitudes,

$$\begin{aligned} \frac{\lambda}{2\pi\epsilon_0 x} &= \frac{\lambda/2}{2\pi\epsilon_0(x-d)}, \\ 2(x-d) &= x, \quad x = 2d. \end{aligned}$$

This satisfies $x > d$. At this location the distances from the wires are $2d$ and d , so both field

magnitudes are $\lambda/(4\pi\epsilon_0 d)$. Reversing both charge signs would reverse both fields without changing this cancellation location.

Step 4: Conclusion The net field is zero in region C, at a perpendicular distance $2d$ from wire 1, or d beyond wire 2.

Quick Tip to Solve: Oppositely charged wires cannot cancel between them; check the exterior on the side of the smaller charge density, using the $1/r$ field law.

27. (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?

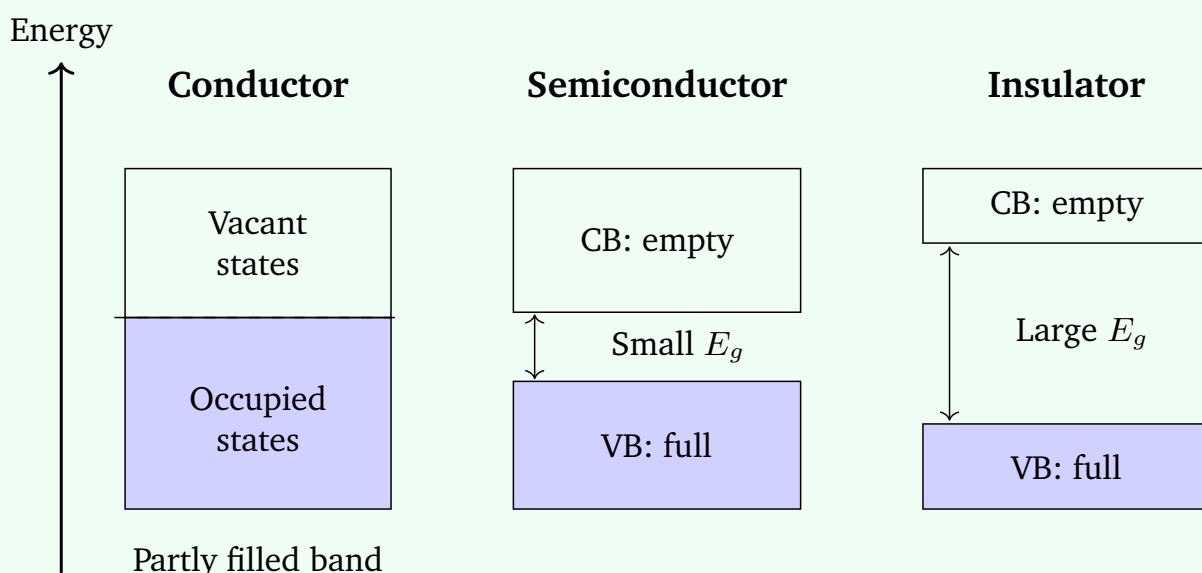
(b) Carbon and silicon both, are members of IV group of periodic table and have the same lattice structure. Carbon is an insulator whereas silicon is a semiconductor. Explain. [3 marks]

Solution:

Concept:

- The valence band (VB) contains bonding electron states; the conduction band (CB) contains states in which electrons can conduct. The forbidden energy gap is $E_g = E_C - E_V$, where E_C and E_V are the relevant band edges.
- At $T = 0$ K, an intrinsic semiconductor and an insulator have a full VB and an empty CB. A metal has a partly filled allowed band or overlapping bands with accessible empty states.

Step 1: Draw and compare the bands at zero temperature In the diagram, vertical position represents increasing electron energy. The conductor is represented by a partly filled allowed band: occupied states have vacant states immediately above them within the same band, so no forbidden gap prevents conduction. A semiconductor has a small forbidden gap, while an insulator has a much larger gap. Their valence bands are completely filled and their conduction bands empty at 0 K; neither has thermally generated charge carriers at that temperature.



Schematic energy bands at $T = 0$ K; blue shading denotes occupied states. Gap sizes are qualitative.

Step 2: Explain electron-hole pair formation at room temperature Thermal energy can excite some valence electrons across the small forbidden gap of a semiconductor into its conduction band. Each

excited electron leaves a vacant state, called a hole, in the valence band. The conduction electron and its associated hole constitute an electron-hole pair. The electron contributes to conduction in the CB; movement of other valence electrons into the vacancy makes the hole behave as a positive charge carrier. In a pure semiconductor, thermal generation creates equal numbers of electrons and holes.

Step 3: Explain why diamond and silicon differ The carbon referred to here is diamond, whose lattice structure is like that of silicon. Although both atoms have four valence electrons, the smaller carbon atom holds its valence electrons more tightly and forms stronger covalent bonds. Diamond has a large band gap, approximately 5.4 eV, whereas silicon has a much smaller gap, approximately 1.1 eV at room temperature. Ordinary thermal excitation produces an appreciable carrier population in silicon but a negligible one in diamond. Thus equal valency and similar crystal structure do not imply equal band gaps or equal electrical conductivity.

Step 4: Conclusion A conductor has accessible vacant states within an allowed band; semiconductors and insulators have small and large forbidden gaps respectively. Thermal excitation across the small gap forms electron-hole pairs in silicon, while diamond's large gap makes it an insulator.

Quick Tip to Solve: In a zero-temperature band sketch, show a full VB and empty CB for both silicon and diamond; distinguish them by the gap width, not by filling.

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]

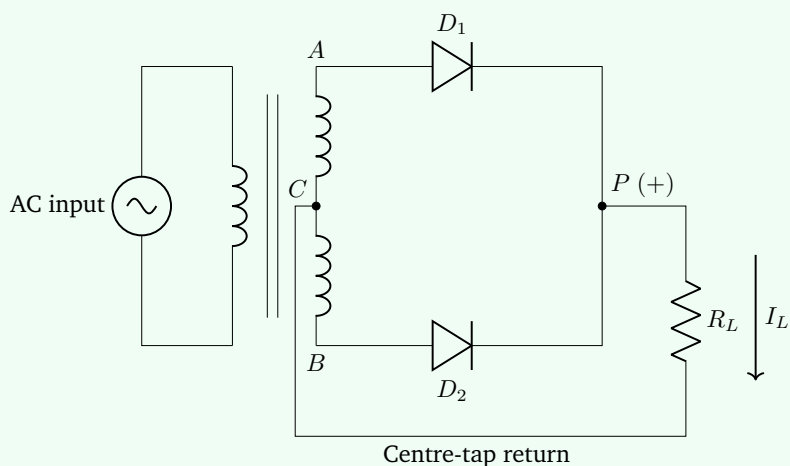
Solution:

Concept:

- A junction diode conducts when forward biased and blocks current when reverse biased. Rectification uses this property to turn alternating current into unidirectional, pulsating current.
- In a centre-tapped full-wave rectifier, the two ends of the secondary have opposite instantaneous polarities relative to the centre tap. Two diodes conduct alternately, maintaining the same direction of load current.

Step 1: Compare the two forms of rectification A half-wave rectifier uses only one half-cycle of the alternating input; the other half-cycle gives no load current. A full-wave rectifier uses both half-cycles and gives load current in the same direction during each. For an input frequency f , the pulsating output repeats at f for half-wave rectification and at $2f$ for full-wave rectification. Full-wave rectification therefore gives a less interrupted output that is easier to smooth. The usual half-wave circuit has one diode, while the centre-tapped full-wave circuit below has two.

Step 2: Connect the centre-tapped secondary and load Connect the ends A and B of a transformer secondary 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 , which is the return terminal. The transformer primary receives the alternating input.



Centre-tapped full-wave rectifier; load current has the indicated direction in both half-cycles.

Step 3: Follow the current through each half-cycle When A is positive relative to C , B is negative. Diode D_1 is forward biased and D_2 is reverse biased. Current follows $A \rightarrow D_1 \rightarrow P \rightarrow R_L \rightarrow C$. During the next half-cycle, B is positive relative to C . Diode D_2 conducts and D_1 blocks. Current follows $B \rightarrow D_2 \rightarrow P \rightarrow R_L \rightarrow C$. Thus, the current through R_L flows from P towards C in both half-cycles. Without a filter, its magnitude still varies with time.

Step 4: Conclusion Half-wave rectification uses one half-cycle, whereas full-wave rectification uses both. The two diodes in the centre-tapped circuit conduct alternately and produce a unidirectional pulsating output of frequency $2f$.

Quick Tip to Solve: Trace each conducting loop separately: both must cross the load from the joined diode cathodes towards the centre tap.

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. 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]

29(i)(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 is converted into a voltmeter by placing a high resistance in series with its coil.
- The full-scale voltage is $V = I_g(G + R)$, where G is the galvanometer resistance, R the external series resistance and I_g the unchanged full-scale current.

Step 1: Write the two full-scale voltage equations The same galvanometer reaches full-scale deflection at the same current in both arrangements. Therefore

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

Doubling the range requires doubling the total series resistance, which includes the coil resistance.

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

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

Option (B) misses the factor of two multiplying R_1 . Options (C) and (D) do not satisfy the doubled total-resistance condition. A physical positive coil resistance also requires $R_2 > 2R_1$.

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

Quick Tip to Solve: When a voltmeter range doubles, double the coil-plus-series resistance; the coil resistance is present in both arrangements.

OR

29(i)(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:

- In the radial magnetic field of a moving-coil galvanometer, the deflecting torque is $\tau = NBIA$, where N is the number of turns, B the field, I the coil current and A the area of each turn.
- All quantities must be in SI units: $1 \text{ mA} = 10^{-3} \text{ A}$ and $1 \text{ cm}^2 = 10^{-4} \text{ m}^2$.

Step 1: Convert current and area to SI units Use $N = 100$, $B = 0.20 \text{ T}$, $I = 5 \times 10^{-3} \text{ A}$ and $A = 18 \times 10^{-4} \text{ m}^2$. The area conversion is squared because both length dimensions change from centimetres to metres.

Step 2: Substitute in the magnetic torque formula In a radial field the coil's magnetic moment remains perpendicular to the field, so the torque factor is unity:

$$\tau = 100 \times 0.20 \times (5 \times 10^{-3}) \times (18 \times 10^{-4})$$
$$= 1.8 \times 10^{-4} \text{ N m}.$$

Options (A) and (C) are too large and option (D) has the wrong coefficient. No extra angular factor or second factor of the number of turns is needed.

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: Convert square centimetres using a factor of 10^{-4} , then use $NBIA$ directly for the radial field of a galvanometer.

29(ii). 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 effective resistance of an ammeter made from a galvanometer and parallel shunt is $R_A = GS/(G + S)$.
- At full scale, its terminal voltage is $V = I_g G$, so an equivalent expression is $R_A = I_g G/I$, where I is the total current.

Step 1: Identify the numerical ammeter data The printed question refers to case (ii), which is this part itself. The numerical ammeter described in the adjoining printed part (iii) supplies the intended data: $G = 6\ \Omega$, $I_g = 0.2\text{ A}$, and range $I = 5\text{ A}$. Its full-scale voltage is

$$V = I_g G = 0.2 \times 6 = 1.2\text{ V}.$$

Step 2: Calculate the effective ammeter resistance The resistance of the complete instrument uses the total current, not just the current through the coil:

$$R_A = \frac{V}{I} = \frac{1.2}{5} = 0.24\ \Omega.$$

This also follows from $6 \times 0.25/(6 + 0.25)$. Option (A) confuses the numerical current with resistance; option (C) is the coil resistance alone; option (D) adds the parallel branch resistances as though they were in series.

Step 3: Conclusion For the numerical ammeter described in printed part (iii), the effective resistance is $0.24\ \Omega$. Hence, the correct option is (B).

Quick Tip to Solve: For a converted ammeter, divide the galvanometer's full-scale voltage by the full ammeter current to get its effective resistance.

29(iii). 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 shunt of resistance S is connected in parallel with a galvanometer of resistance G to carry the excess current.
- Equal potential differences across the parallel branches give $I_g G = (I - I_g)S$, where I_g is the galvanometer full-scale current and I is the required ammeter range.

Step 1: Determine the current through the shunt At the upper limit of the ammeter range, the total current is $5\ \text{A}$, while only $0.2\ \text{A}$ may pass through the galvanometer. The remaining current must flow through the shunt:

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

Step 2: Equate the voltage across the two branches The galvanometer voltage at full scale is $I_g G = 0.2 \times 6 = 1.2\ \text{V}$. Thus

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

Options (B) and (C) would carry too little shunt current at this voltage; option (D) would divide the current equally between the two equal resistances and cannot give the required range.

Step 3: Conclusion The required parallel shunt is $0.25\ \Omega$. Hence, the correct option is (A).

Quick Tip to Solve: Subtract the galvanometer current from the desired range before dividing the full-scale voltage by the shunt current.

29(iv). 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: $S_I = \phi/I$.
- In a radial magnetic field, equilibrium requires $NBAI = k\phi$, where N is the turn count, B is the

field, A is each turn's area and k is the spring's torsional constant.

Step 1: Isolate the deflection per unit current Divide the torque-balance equation by kI :

$$\frac{\phi}{I} = \frac{NBA}{k}.$$

Sensitivity increases when a given current produces a larger angular deflection. Increasing N , B or A increases the magnetic torque and therefore increases this sensitivity.

Step 2: Check the alternative expressions A stiffer spring, with larger k , requires more current for the same deflection; consequently k must appear in the denominator. Option (A) is the reciprocal sensitivity, or current per unit deflection. Options (C) and (D) place k in the numerator and also give the wrong dependence on the coil geometry or turn count.

Step 3: Conclusion The current sensitivity is $S_I = NBA/k$, measured in radians per ampere. Hence, the correct option is (B).

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

30. 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]

30(i). (i) 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:

- Einstein's equation is $K_{\max} = h\nu - \phi$, where h is Planck's constant, ν the incident frequency and ϕ the metal's work function.
- The magnitude of the stopping or cut-off potential V_0 obeys $eV_0 = K_{\max}$, where e is the elementary charge.

Step 1: Relate cut-off potential to frequency Combine the energy and stopping-potential equations to obtain

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

Thus a plot of cut-off potential against incident frequency is a straight line. Its gradient has the known factor $1/e$ multiplying the desired constant h .

Step 2: Identify the useful gradient If the gradient is $m = \Delta V_0 / \Delta \nu$, then $h = em$. Photocurrent

versus intensity measures the electron emission rate, not this energy gradient. Photocurrent versus frequency does not directly give h/e ; and changing intensity at fixed frequency does not change the stopping potential.

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: For a stopping-potential graph the slope is h/e ; multiply by e to find Planck's constant.

30(ii)(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 incident frequency and ϕ is the metal's work function.
- For the same metal, the maximum photoelectron energy increases with frequency; intensity controls the number emitted, not their maximum kinetic energy.

Step 1: Compare the incident frequencies Visible wavelengths decrease from red through yellow to blue. Since $\nu = c/\lambda$, the frequency order is $\nu_B > \nu_Y > \nu_R$. Equal intensity does not make these photon energies equal.

Step 2: Apply the same work function Subtracting the same ϕ from the three photon energies preserves their ordering. For the photoemission stated in the question, $K_B - K_Y = h(\nu_B - \nu_Y) > 0$ and $K_Y - K_R = h(\nu_Y - \nu_R) > 0$. Options (A) and (D) wrongly place red first, while (B) wrongly places yellow above blue.

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

Quick Tip to Solve: For one metal, rank maximum photoelectron energies by frequency: blue exceeds yellow, which exceeds red.

30(ii)(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:

- Photoemission requires $h\nu \geq \phi$, where ϕ is the work function and $h\nu$ is a photon's energy.
- The threshold frequency is $\nu_0 = \phi/h$. A low work function permits photoemission at lower frequencies, including suitable visible frequencies.

Step 1: Identify the low-work-function metal Caesium is an alkali metal with a low work function, approximately 2 eV. Visible photons at sufficiently high frequency can therefore supply enough energy to liberate electrons from its surface.

Step 2: Eliminate the other metals Zinc, cadmium and magnesium have appreciably higher work functions and ordinarily require ultraviolet radiation for photoemission. Increasing the intensity of visible light would increase the photon number but would not increase an individual photon's energy enough to cross their thresholds. Thus the low threshold of caesium is the decisive property.

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, choose the low-work-function alkali metal among these options.

30(iii). (iii) 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 the anode collects all the emitted photoelectrons: $I_s = e\dot{N}$, where $\dot{N}$ is the number collected per second.
- In the standard CBSE photoelectric-effect comparison, intensity controls saturation current, while frequency controls maximum kinetic energy and stopping potential.

Step 1: Keep the stated intensity fixed The question uses the usual textbook experimental rule: at the same incident intensity, the saturation-current level is unchanged when frequency changes, provided the light remains above the threshold frequency. Increasing frequency alone is not taken to increase

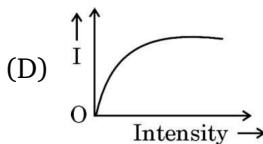
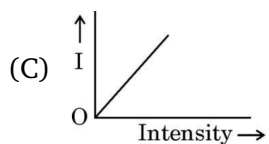
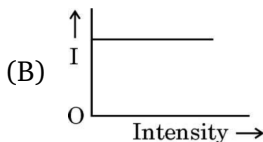
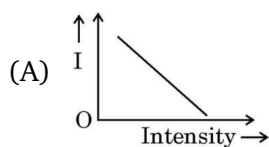
the rate of emission in this comparison.

Step 2: Distinguish electron energy from current Einstein's relation $K_{\max} = h\nu - \phi$ shows that the emitted electrons become more energetic when ν increases. A larger kinetic energy changes the stopping potential; it does not make more than all the emitted electrons reach the anode at saturation. Thus neither linear nor nonlinear growth of saturation current is the textbook result, and a decrease is not the intended dependence.

Step 3: Conclusion With intensity unchanged, the saturation current remains the same in the stated textbook comparison. Hence, the correct option is (D).

Quick Tip to Solve: Compare saturation levels using intensity; compare stopping potentials using frequency above threshold.

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



Correct Answer: (C)

Solution:

Concept:

- At fixed incident frequency above threshold, increasing light intensity increases the number of photons incident per second.
- With the metal and collection conditions fixed, photoelectric current $I = e\dot{N}_e$ is proportional to the rate $\dot{N}_e$ of collected photoelectrons, where e is the elementary charge.

Step 1: Relate intensity to the emission rate Each photon has the same energy $h\nu$ at fixed frequency. Doubling the light intensity therefore doubles the incident photon rate and hence the photoelectron rate under the same conditions. Consequently, the current increases in direct proportion to light intensity.

Step 2: Compare the four graphs Direct proportionality gives a straight line with positive slope through the origin. Graph (A) wrongly shows decreasing current, (B) wrongly shows constant current and (D) wrongly shows a progressively flattening curve. Graph (C) alone has the required straight-line increase. Saturation with increasing collecting voltage must not be confused with this intensity

variation.

Step 3: Conclusion Photoelectric current is directly proportional to light intensity, as in graph (C). Hence, the correct option is (C).

Quick Tip to Solve: Check the horizontal axis: varying intensity gives a straight rising line, while varying collector voltage may give saturation.

Section E (15 marks)

31(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.

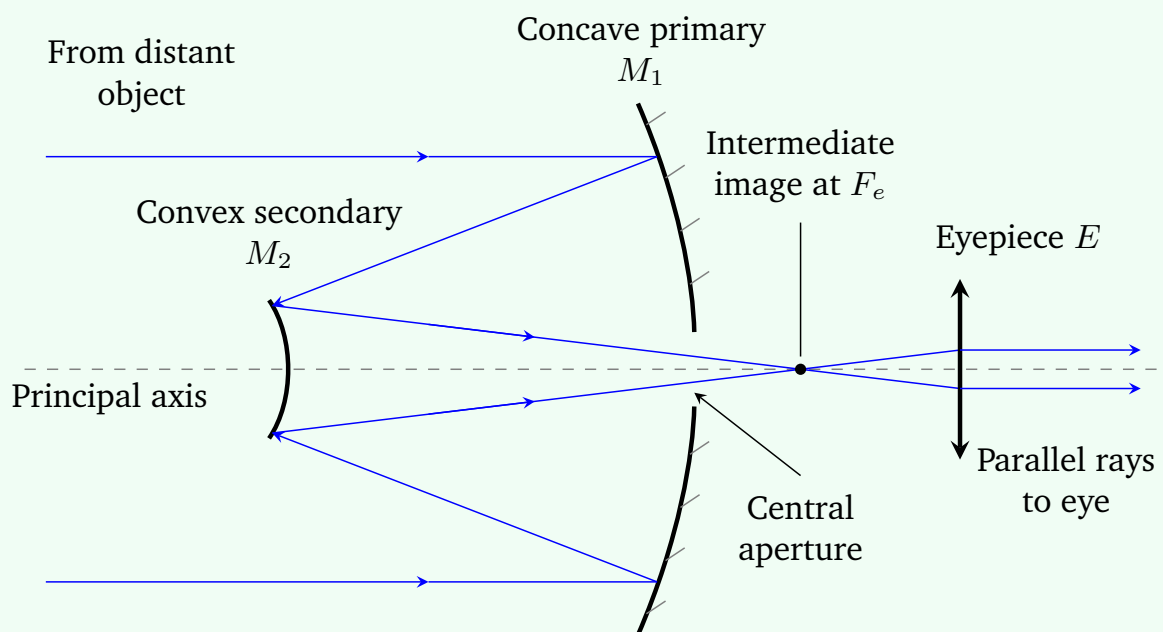
(ii) In a refracting telescope, the focal length of the objective is 50 times the focal length of the eyepiece. When the final image is formed at infinity, the length of the tube is 102 cm. Find the focal lengths of the two lenses. [5 marks]

Solution:

Concept:

- A Cassegrain telescope uses a large concave primary mirror to collect light and a small convex secondary mirror to redirect the converging beam through a central hole in the primary.
- The eyepiece magnifies the real intermediate image. For relaxed viewing, that image lies in the first focal plane of the eyepiece, so the final virtual image is at infinity.
- For a refracting astronomical telescope in normal adjustment, $L = f_o + f_e$, where L is the lens separation and f_o, f_e are the positive focal lengths of its objective and eyepiece.

Step 1: (i) Trace the rays through the Cassegrain telescope Parallel rays from a distant object fall on the large concave primary mirror M_1 . After reflection they converge toward its focus. Before they reach that focus, a small convex secondary mirror M_2 intercepts the beam and reflects it back toward the primary. The rays pass through the central aperture of M_1 and converge behind it to form a real intermediate image. The schematic traces an axial pencil of rays; for an extended distant object the intermediate image is inverted.



Cassegrain telescope: axial ray path through the primary aperture to the intermediate image at F_e , followed by the eyepiece E (schematic, not to scale).

Step 2: Explain viewing through the eyepiece The eyepiece E , placed behind the primary mirror, acts as a magnifier of the intermediate image. In normal adjustment, the intermediate image lies at its first focal plane F_e . The emerging rays are then parallel, and the observer sees an angularly magnified, inverted virtual image at infinity. The secondary mirror folds the light path, allowing a long effective focal length within a relatively short tube.

Step 3: State two advantages over a refracting telescope 1. **Absence of chromatic aberration from the objective:** reflection does not separate colours as refraction through a lens does. Consequently, a mirror objective brings different wavelengths to the same focus.

2. **A larger practical aperture:** a mirror can be supported from its back, whereas a large objective lens has to be supported at its rim. Large mirrors can therefore be made and supported more easily. Their greater aperture collects more light from faint objects and improves the angular resolving power.

Step 4: (ii) Use the focal-length ratio and tube length For the separate refracting telescope described in part (ii), the given ratio is $f_o = 50f_e$. Since the final image is at infinity, the image formed by the objective is at the eyepiece's first focus. Hence the two focal lengths add to the tube length:

$$\begin{aligned} L &= f_o + f_e = 102 \text{ cm}, \\ 50f_e + f_e &= 102 \text{ cm}, \\ 51f_e &= 102 \text{ cm}, \\ f_e &= \frac{102}{51} \text{ cm} = 2 \text{ cm}, \\ f_o &= 50(2 \text{ cm}) = 100 \text{ cm}. \end{aligned}$$

The values satisfy both checks: their sum is 102 cm, and the objective focal length is fifty times the eyepiece focal length.

Step 5: Conclusion The Cassegrain arrangement forms its intermediate image behind the primary mirror and uses an eyepiece to obtain the final magnified view. Its main advantages are an achromatic mirror objective and a large practical aperture. For the refracting telescope, $f_o = 100 \text{ cm}$, $f_e = 2 \text{ cm}$.

Quick Tip to Solve: When the final image is at infinity, combine the ratio with $f_o + f_e = L$: if $f_o = nf_e$, then $f_e = L/(n + 1)$. In a Cassegrain sketch, show the secondary sending light through the primary's central hole.

OR

31(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_1 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 an objective to form a real enlarged intermediate image, which the eyepiece magnifies again. Its angular magnification magnitude is $M = |m_o|M_e$.
- For the final image at the near point, $M_e = 1 + D/f_e$, where D is the least distance of distinct vision and f_e is the eyepiece focal length.
- For a thin lens in air, $P = 1/f = (n - 1)(1/R_1 - 1/R_2)$. Powers of thin lenses in contact add: $P = P_1 + P_2$; radii must be in metres to obtain dioptres.

Step 1: (i) State two advantages First, the compound microscope provides much greater magnification because the objective's linear magnification is multiplied by the eyepiece's angular magnification. A

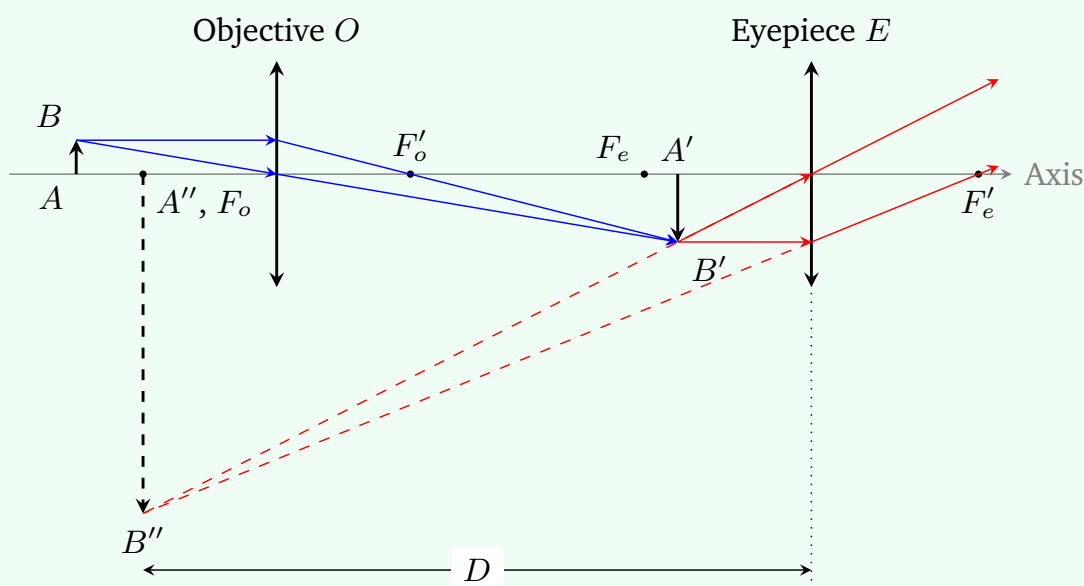
simple microscope gives only the angular magnification of one lens. Second, a compound microscope can provide greater resolving power, using a suitably designed objective of high numerical aperture; it therefore reveals finer details and distinguishes closer points in a specimen. This improvement comes from the objective's light-gathering angle and optical design, rather than from increasing magnification alone.

Step 2: (i) Explain image formation at the near point Place the small object AB just beyond the first principal focus F_o of the objective O . The objective forms a real, inverted and enlarged image $A'B'$. Adjust the eyepiece E so that $A'B'$ lies between its first focus F_e and its optical centre. Thus the eyepiece acts as a simple magnifier.

Rays emerging from the eyepiece diverge; their backward extensions meet at B'' . The resulting image $A''B''$ is virtual, further enlarged and inverted relative to the original object. Its distance from the eyepiece is D , the near-point distance (approximately 25 cm for a normal eye). The solid rays show real propagation; dashed lines show backward extensions. The diagram selects two rays for each imaging stage.

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

Here u_o and v_o are the objective's object and image distances; the image inversion supplies a negative sign if signed magnification is used.



Compound microscope with the final virtual image at the near point. The diagram is schematic; $EA'' = D$.

Step 3: (ii) Find the planoconcave lens power Take light travelling from left to right and let $R > 0$ denote the given radius magnitude. Orient the planoconcave lens with its plane face first. Then $R_1 = \infty$ and $R_2 = +R$, because the centre of curvature of its second, concave surface lies to its right. Therefore,

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

The negative sign is consistent with this lens being diverging. Reversing its orientation would give the same power.

Step 4: (ii) Add the equiconvex lens power For the equiconvex lens, the first surface has $R_1 = +R$,

and the second has $R_2 = -R$. Hence,

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

Since the lenses are thin and coaxial in contact, there is no separation term in the equivalent power:

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

The combination is converging, diverging or of zero power according as $2n_2 - n_1 - 1$ is positive, negative or zero.

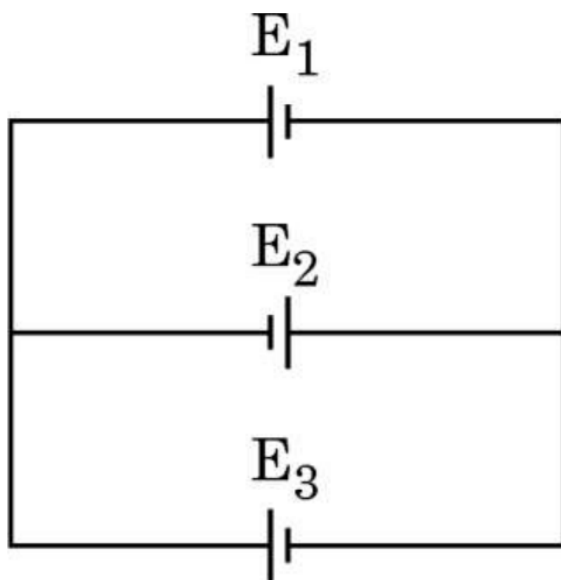
Step 5: Conclusion The compound microscope offers higher magnification and, with an appropriate objective, finer resolution. Its near-point image is virtual, enlarged and inverted. The contact combination has power $P = (2n_2 - n_1 - 1)/R$ dioptries when R is in metres.

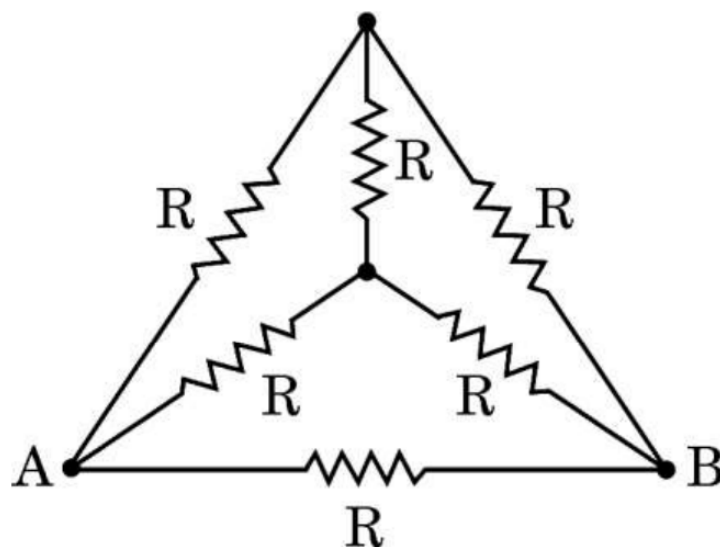
Quick Tip to Solve: For the microscope, place the intermediate image inside the eyepiece focal length. For the lens pair, assign signed radii separately and add powers, not focal lengths.

32(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 a node is zero, as charge cannot accumulate in a steady circuit.
- The longer plate of a cell is its positive terminal. For current I taken from left to right through a branch with positive terminal on the left, the common node voltage satisfies $V_L - V_R = E + Ir$, where r is the internal resistance.
- Equal-resistance bridge arms give equal potentials at their intermediate nodes; no current then flows through the bridge resistor. Series resistances add, while parallel conductances add.

Step 1: (i) Read the battery polarities and define the currents Let $V = V_L - V_R$ be the potential difference between the common left and right junctions. Take all branch currents I_1, I_2, I_3 as positive from left to right. The printed longer plates show that E_1 and E_3 have positive terminals on the left, while E_2 has its positive terminal on the right. Thus the middle emf has the opposite sign in the branch equations:

$$I_1 = \frac{V - 4}{2}, \quad I_2 = \frac{V + 2}{4}, \quad I_3 = \frac{V - 6}{2}.$$

Here emfs and V are in volts, resistances in ohms and the resulting currents in amperes. The internal resistances must be included even though the diagram represents each battery by its cell symbol.

Step 2: Apply the junction rule and determine the directions There is no external current entering either junction, so

$$\begin{aligned} \frac{V - 4}{2} + \frac{V + 2}{4} + \frac{V - 6}{2} &= 0, \\ 2(V - 4) + (V + 2) + 2(V - 6) &= 0, \\ 5V - 18 &= 0, \quad V = 3.6 \text{ V}. \end{aligned}$$

Substituting this common terminal voltage into the three branches gives

$$\begin{aligned} I_1 &= \frac{3.6 - 4}{2} = -0.20 \text{ A}, \\ I_2 &= \frac{3.6 + 2}{4} = 1.40 \text{ A}, \\ I_3 &= \frac{3.6 - 6}{2} = -1.20 \text{ A}. \end{aligned}$$

Negative values reverse the assumed direction. Hence the top and bottom batteries carry current right to left, whereas the middle battery carries current left to right. The junction check is $0.20 + 1.20 = 1.40$ A.

Step 3: (ii) Identify the balanced bridge in the wire network Call the top vertex C and the central junction D . The four arms AC, CB, AD, DB each have resistance R . Their ratios satisfy

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

Therefore C and D are at the same potential for a voltage applied between A and B . The wire CD has zero potential difference across it and carries no current; it may be omitted when calculating the effective resistance.

Step 4: Combine the three remaining parallel paths The direct path AB has resistance R . The paths ACB and ADB each have two series resistances and hence resistance $2R$. All three paths join the same terminals, so

$$\begin{aligned}\frac{1}{R_{\text{eff}}} &= \frac{1}{R} + \frac{1}{2R} + \frac{1}{2R} = \frac{2}{R}, \\ R_{\text{eff}} &= \frac{R}{2} = \frac{10}{2} \Omega = 5 \Omega.\end{aligned}$$

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 between A and B is 5Ω .

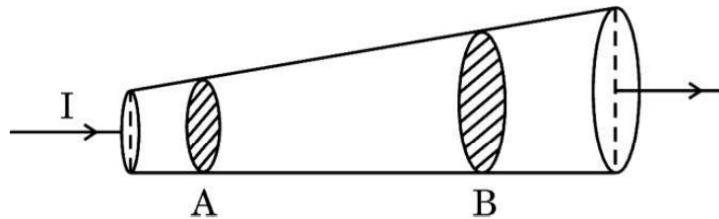
Quick Tip to Solve: Check the longer plate before assigning each emf sign: the middle battery is reversed. In the six-wire network, remove only the zero-current bridge, then include the direct AB resistor in parallel.

32(b). (i) Current $I (= 1 \text{ A})$ 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:

- For steady current I in a conductor of local cross-sectional area A , the current density is $J = I/A$. Ohm's law in microscopic form is $E = \rho J$, where ρ is the resistivity.
- The magnitude of the electron drift velocity is $v_d = I/(neA)$, where n is the free-electron number density and e is the magnitude of the electronic charge. Electrons drift opposite to conventional current.
- A point charge produces $\vec{E} = kq(\vec{r} - \vec{r}_q)/|\vec{r} - \vec{r}_q|^3$, where $k = 1/(4\pi\epsilon_0)$. Electric fields add vectorially by superposition.

Step 1: (i)(I) Relate the electric field to cross-sectional area In the steady state the same current passes through every cross-section; otherwise charge would continue accumulating within the rod. The rod is copper throughout, so its resistivity is the same at A and B , under the usual uniform-temperature assumption. Since $E = \rho I/A$,

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

The smaller cross-section therefore requires twice the electric field to sustain the same current. The required field ratio is $E_A : E_B = 2 : 1$.

Step 2: (i)(II) Calculate the electron drift speed at B Use the area at B , namely $A_B = 2.0 \times 10^{-7} \text{ m}^2$, with $n = 8.5 \times 10^{28} \text{ m}^{-3}$, $I = 1 \text{ A}$ and $e = 1.6 \times 10^{-19} \text{ C}$:

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

This is the magnitude of the average directed electron velocity. Conventional current in the figure is to the right, so the electron drift velocity is to the left.

Step 3: (ii) Find the field due to the first charge The observation point is $P = (3, 4)$ m, whereas q_1 is at $(3, 0)$ m. The displacement from q_1 to P is therefore $4\hat{j}$ m, with magnitude 4 m. Since $q_1 = 16 \times 10^{-6}$ C is positive, its field points away from it, along the positive y -axis:

$$\vec{E}_1 = \frac{(9 \times 10^9)(16 \times 10^{-6})}{4^2} \hat{j} = 9.0 \times 10^3 \hat{j} \text{ N C}^{-1}.$$

Step 4: Find the second field and apply superposition The second charge is at $(0, 4)$ m, so the displacement from q_2 to P is $3\hat{i}$ m, with magnitude 3 m. As $q_2 = 1 \times 10^{-6}$ C is also positive, its field is along the positive x -axis:

$$\vec{E}_2 = \frac{(9 \times 10^9)(1 \times 10^{-6})}{3^2} \hat{i} = 1.0 \times 10^3 \hat{i} \text{ N C}^{-1}.$$

The two fields are perpendicular, so their magnitudes cannot simply be added. Their vector sum is

$$\vec{E} = \vec{E}_1 + \vec{E}_2 = (1.0 \times 10^3 \hat{i} + 9.0 \times 10^3 \hat{j}) \text{ N C}^{-1}.$$

As a check, its magnitude is $\sqrt{82} \times 10^3 \simeq 9.06 \times 10^3 \text{ N C}^{-1}$, directed at $\tan^{-1}(9) \simeq 83.7^\circ$ above the positive x -axis.

Step 5: Conclusion (i)(I) $E_A : E_B = 2 : 1$. (i)(II) The electron drift speed at B is $3.68 \times 10^{-4} \text{ m s}^{-1}$, opposite to the current. (ii) The net 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 steady current, both electric field and drift speed vary as $1/A$. For the point charges, subtract each source position from the observation position before using the inverse-square law.

33(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:

- Self-inductance relates a coil's total magnetic flux linkage $N\Phi$ to the current I : $N\Phi = LI$, for constant inductance L .
- The self-induced emf is $\varepsilon = -L dI/dt$. The minus sign expresses opposition to the change of current, so the external source must do work against this back emf.

- For an ideal inductor, the work supplied while establishing the current is stored in its magnetic field as $U = \frac{1}{2}LI^2$.

Step 1: (i) Define self-inductance The self-inductance of a coil is its magnetic flux linkage per unit current:

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

Here N is the number of turns and Φ is the magnetic flux through each turn. Equivalently, it is the magnitude of the induced emf per unit rate of change of current, $L = |\varepsilon|/|dI/dt|$. Its SI unit is the henry (H). A coil has self-inductance 1 H if a current changing at 1 A s^{-1} induces an emf of magnitude 1 V in it.

Step 2: (i) Derive the energy required to establish the current Let the instantaneous current be i , increasing from zero to I , and let L remain constant. The back emf has magnitude $L di/dt$. The applied voltage needed to overcome this emf is therefore $V = L di/dt$. In a small interval dt , the charge passing through the coil is $dq = i dt$, so the work done against the back emf is

$$dW = V dq = \left(L \frac{di}{dt} \right) i dt = Li di.$$

Integrating over the buildup of current gives

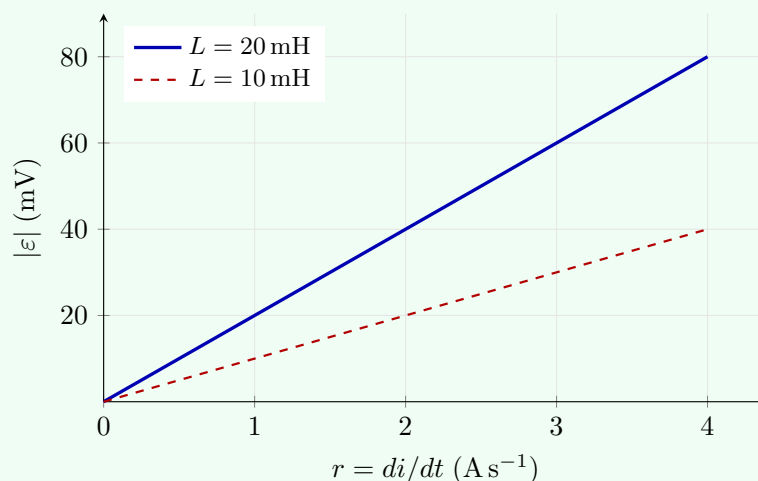
$$W = \int_0^I Li di = \frac{1}{2}LI^2.$$

This work is stored as magnetic-field energy. The derivation assumes an ideal coil: any additional energy dissipated as heat in a real coil's resistance is separate from the energy stored in its field. Since $L > 0$, the stored energy is positive irrespective of the current's direction.

Step 3: (ii) (I) Plot induced-emf magnitude against rate of current change Put $r = di/dt \geq 0$, since the currents are increasing. For the two coils,

$$|\varepsilon_{10}| = (0.010 \text{ H})r, \quad |\varepsilon_{20}| = (0.020 \text{ H})r.$$

Both graphs are straight lines through the origin because induced-emf magnitude is proportional to r . Their slopes are the respective self-inductances. Thus the line for 20 mH has twice the slope of the line for 10 mH. At the same rate of current change, the emf magnitude in the former is twice that in the latter. The plotted scale uses millivolts, so a rate of 1 A s^{-1} corresponds to 10 mV and 20 mV, respectively.

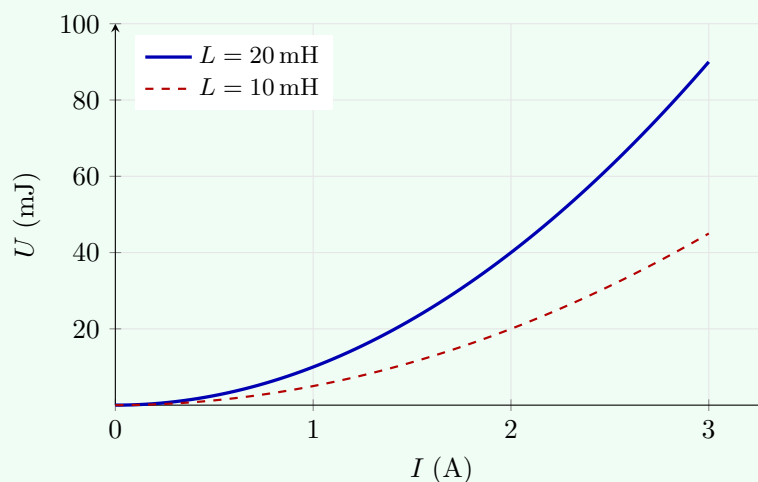


Induced-emf magnitude versus the rate of increase of current.

Step 4: (ii)(II) Plot stored energy against current For each coil use $U = \frac{1}{2}LI^2$:

$$U_{10} = (0.005 \text{ H})I^2, \quad U_{20} = (0.010 \text{ H})I^2.$$

Each energy-current graph is an upward-opening parabola through the origin, with a horizontal tangent there. For positive current the energy rises increasingly rapidly. At any fixed nonzero current, $U_{20}/U_{10} = 2$, so the 20 mH curve lies above the 10 mH curve. For example, at $I = 1 \text{ A}$, the energies are 10 mJ and 5 mJ, respectively. The positive-current branches are shown; if negative currents are included, the curves are symmetric about the energy axis because energy depends on I^2 .



Magnetic energy versus current, showing the positive-current branches.

Step 5: Conclusion Self-inductance is $L = N\Phi/I$, and the energy required to build the magnetic field is $U = \frac{1}{2}LI^2$. The emf-rate graphs are straight lines through the origin, with slope proportional to L ; the energy-current graphs are parabolas. At the same rate or the same current, respectively, the 20 mH inductor has twice the induced-emf magnitude or stored energy of the 10 mH inductor.

Quick Tip to Solve: Read the horizontal axis first: emf versus dI/dt is linear, whereas energy versus I is quadratic. Doubling L doubles the vertical value in both graphs.

- 33(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 magnetic flux linkage of one coil per unit current in the other: $N_2\Phi_{21} = MI_1$. Here Φ_{21} is flux through one turn of coil 2 due to current I_1 in coil 1.
- An ideal long air-core solenoid with N turns, length ℓ , and current I produces $B = \mu_0 NI/\ell$ inside; its external field is negligible.
- For an inductor, the total self-flux linkage is $\lambda = LI$, and the induced emf is $\varepsilon = -d\lambda/dt = -L dI/dt$. The minus sign expresses Lenz's law.

Step 1: (i) Define mutual inductance and specify the solenoids The mutual inductance of two coils equals the flux linkage in either coil when unit current flows in the other. Equivalently, its magnitude is the emf induced in one coil per unit rate of change of current in the other:

$$M = \frac{N_2\Phi_{21}}{I_1} = \frac{|\varepsilon_2|}{|dI_1/dt|}.$$

Its SI unit is henry (H). Consider two long coaxial solenoids of common length ℓ , with N_1, N_2 turns and radii $r_1 < r_2$. Let coil 1 be the inner solenoid, with area $A_1 = \pi r_1^2$. Neglect end effects and take the medium to be air.

Step 2: Calculate the flux linkage of the outer solenoid Pass current I_1 through the inner solenoid. Its magnetic field is uniform inside its own cross-section and negligible outside:

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

Although the outer turns enclose a larger area, the field from the inner solenoid occupies only A_1 . Thus the flux through each outer turn and the total linkage are

$$\begin{aligned}\Phi_{21} &= B_1 A_1, \\ N_2\Phi_{21} &= \frac{\mu_0 N_1 N_2 A_1}{\ell} I_1.\end{aligned}$$

Comparing with $N_2\Phi_{21} = M_{21}I_1$ gives

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

Step 3: Confirm the result when the source current is reversed between coils Now let current I_2 flow in the outer solenoid. Its field $B_2 = \mu_0 N_2 I_2/\ell$ is uniform throughout the inner solenoid. Each inner

turn encloses area A_1 , so

$$N_1 \Phi_{12} = N_1 B_2 A_1 = \frac{\mu_0 N_1 N_2 A_1}{\ell} I_2.$$

Hence $M_{12} = M_{21} = M$. The common linked area is always the smaller cross-section. In terms of turn densities $n_1 = N_1/\ell$ and $n_2 = N_2/\ell$, the same expression is $M = \mu_0 n_1 n_2 A_1 \ell$. For a common uniform magnetic medium, replace μ_0 by its permeability μ .

Step 4: (ii) Determine the self-inductance and current at ten seconds Since the current rises uniformly, its rate of change is constant:

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

Convert the emf to volts and use its magnitude:

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

The current at $t = 10 \text{ s}$ is $I = (0.05)(10) = 0.50 \text{ A}$.

Step 5: Evaluate the flux linked with the inductor The linked flux means the total flux linkage $\lambda = N\Phi$, rather than flux through a single turn. Starting with zero current, its initial self-flux linkage is zero. At ten seconds,

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

This also follows directly by integration: $\lambda = |\varepsilon|t = (5 \times 10^{-3})(10)$. The emf opposes the increasing current; the requested flux-linkage magnitude is positive.

Step 6: Conclusion (i) For long coaxial air-core solenoids, $M = \mu_0 N_1 N_2 A_{\text{smaller}}/\ell$, with $M_{12} = M_{21}$. (ii) The flux linked at $t = 10 \text{ s}$ 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 current, find total flux linkage directly from $\lambda = |\varepsilon|t$.