

CBSE Class 12 Physics Question Paper 2026 with Solution PDF-Set 55/4/1



Question Paper with Solutions

Conducted by the Central Board of Secondary Education (CBSE)

Time Allowed: 3 hours

Maximum Marks: 70

General Instructions

- (i) This question paper contains **33** questions. **All** questions are **compulsory**.
- (ii) 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. Two wires of same length and same area of cross-section but made of different material of resistivities ρ_1 and ρ_2 are connected in series. The equivalent resistivity of the combination is:

[1 mark]

(A) $\frac{1}{2}(\rho_1 + \rho_2)$

(B) $\rho_1 + \rho_2$

(C) $\sqrt{\rho_1 \rho_2}$

(D) $2(\rho_1 + \rho_2)$

Correct Answer: (A) $\frac{1}{2}(\rho_1 + \rho_2)$

Solution:

Concept:

- A uniform wire has resistance $R = \rho L/A$, where ρ is resistivity, L its length and A its cross-sectional area.
- Series resistances add. The equivalent composite wire has the combined length and the same cross-sectional area.

Step 1: Add the two resistances Let each wire have length L and area A . Since the same current passes through both wires in series,

$$R_{\text{eq}} = R_1 + R_2 = \frac{\rho_1 L}{A} + \frac{\rho_2 L}{A} = \frac{(\rho_1 + \rho_2)L}{A}.$$

Step 2: Use the total length of the combination The series combination has length $2L$, so its effective resistivity obeys

$$\rho_{\text{eq}} \frac{2L}{A} = \frac{(\rho_1 + \rho_2)L}{A}.$$

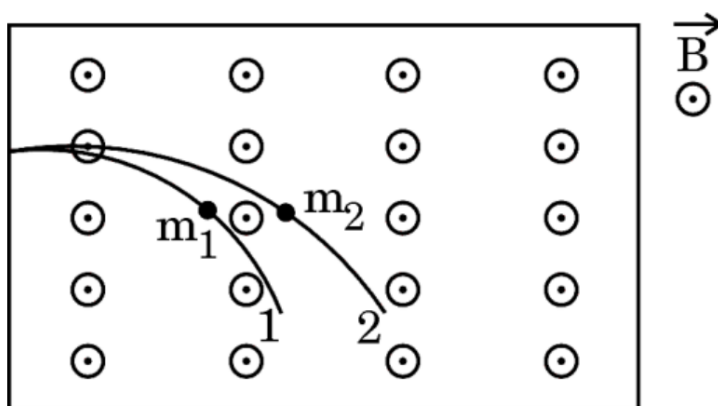
Option (B) overlooks the doubled length; option (D) uses that factor in the wrong direction. The geometric mean in option (C) does not follow from adding series resistances.

Step 3: Conclusion The equivalent resistivity is $\rho_{\text{eq}} = \frac{\rho_1 + \rho_2}{2}$. Hence, the correct option is (A).

Quick Tip to Solve: After adding series resistances, use the total wire length $2L$, not the length of either original wire.

2. Two particles of masses m_1 and m_2 having charges q_1 and q_2 respectively are projected with the same velocity in a region of uniform magnetic field $\vec{B}$ pointing vertically upward. If they describe circular paths as shown in the figure, one may conclude that:

[1 mark]



- (A) $\frac{m_1}{m_2} > \frac{q_1}{q_2}$
 (B) $\frac{m_1}{m_2} > \frac{q_2}{q_1}$
 (C) $\frac{m_1}{m_2} < \frac{q_1}{q_2}$
 (D) $\frac{m_1}{m_2} < \frac{q_2}{q_1}$

Correct Answer: (C) $\frac{m_1}{m_2} < \frac{q_1}{q_2}$

Solution:

Concept:

- For motion perpendicular to a uniform magnetic field, the magnetic force supplies centripetal force: $|q|vB = mv^2/r$.
- Thus the orbit radius is $r = mv/(|q|B)$; at fixed speed v and field strength B , radius measures the mass-to-charge-magnitude ratio.

Step 1: Read the curvatures from the figure Path 1 bends more sharply than path 2, so $r_1 < r_2$. Both particles enter with the same velocity and bend to the same side in the same field. Their charges therefore have the same sign, giving $q_1/q_2 = |q_1|/|q_2| > 0$.

Step 2: Compare their mass-to-charge ratios Applying the radius relation to the two particles gives

$$\frac{r_1}{r_2} = \frac{m_1|q_2|}{m_2|q_1|} < 1.$$

Multiplying by the positive charge-magnitude ratio yields $m_1/m_2 < q_1/q_2$. Option (A) reverses this inequality, while options (B) and (D) compare with the reciprocal charge ratio, which is not what the radius relation gives.

Step 3: Conclusion The figure implies $\frac{m_1}{m_2} < \frac{q_1}{q_2}$. Hence, the correct option is (C).

Quick Tip to Solve: Identify the tighter orbit first: at the same speed and field, it has the smaller $m/|q|$.

3. An electron moves around the nucleus in a circular orbit of radius r and makes n revolutions per second. The value of equivalent current in the orbit is: [1 mark]

- (A) $\frac{e}{n}$
(B) ne
(C) $\frac{ne}{r}$
(D) $\frac{e}{nr}$

Correct Answer: (B) ne

Solution:

Concept:

- Electric current is the charge crossing a fixed point per unit time: $I = Q/t$.
- An orbiting electron of charge magnitude e crosses any chosen point once per revolution. A revolution frequency n corresponds to period $T = 1/n$.

Step 1: Count the charge passing in one second In one second the electron completes n revolutions. Although it is the same electron each time, each passage contributes charge magnitude e to the charge flow. Thus the charge passing a fixed point in one second is ne .

Step 2: Apply the current definition Equivalently, use the time for one revolution:

$$I = \frac{e}{T} = \frac{e}{1/n} = ne.$$

The radius does not appear because the revolution frequency is already specified, ruling out (C) and (D). Option (A) divides by frequency instead of by period; its units are not amperes. Conventional current runs opposite to the electron's direction of motion, but its magnitude is positive.

Step 3: Conclusion The equivalent current has magnitude $I = ne$. Hence, the correct option is (B).

Quick Tip to Solve: For one circulating charge, multiply its magnitude by the number of revolutions per second: $I = ef$.

4. The dimensions of the rate of change of magnetic flux are: [1 mark]

- (A) $[MLT^{-3}A]$
(B) $[ML^2T^{-3}A^{-1}]$
(C) $[ML^2T^{-2}A^{-1}]$
(D) $[ML^2T^{-3}A^{-2}]$

Correct Answer: (B) $[ML^2T^{-3}A^{-1}]$

Solution:

Concept:

- Faraday's law for one turn is $\varepsilon = -d\Phi_B/dt$, so the rate of change of magnetic flux has the dimensions of electromotive force.
- Electromotive force is energy per unit charge. Energy has dimensions $[ML^2T^{-2}]$, while charge has dimensions $[AT]$.

Step 1: Relate the flux rate to voltage The minus sign in Faraday's law describes direction and has no

dimensions. Hence,

$$\left[\frac{d\Phi_B}{dt} \right] = [\varepsilon] = \frac{[\text{energy}]}{[\text{charge}]}$$

Here M, L, T denote the dimensions of mass, length and time, and A denotes electric current.

Step 2: Divide the dimensional expressions Substituting the dimensions of energy and charge gives

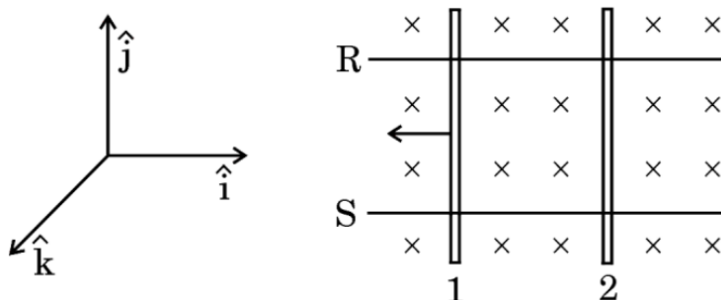
$$[\varepsilon] = \frac{[ML^2T^{-2}]}{[AT]} = [ML^2T^{-3}A^{-1}].$$

Option (C) is the dimension of magnetic flux itself and lacks the additional inverse time. Option (A) has incorrect powers of length and current; option (D) has an extra inverse-current factor.

Step 3: Conclusion The required dimensions are $[ML^2T^{-3}A^{-1}]$. Hence, the correct option is (B).

Quick Tip to Solve: Replace the rate of change of magnetic flux by voltage using Faraday's law, then use energy divided by charge.

5. Two identical conductors 1 and 2 are placed on two frictionless conducting rails R and S in a uniform magnetic field directed vertically downward into the plane of the page. If conductor 1 is moved with a constant velocity in the direction as shown in figure, the force on conductor 2 will be along: [1 mark]



- (A) $-\hat{i}$
- (B) $-\hat{j}$
- (C) $\hat{k}$
- (D) $\hat{j}$

Correct Answer: (A) $-\hat{i}$

Solution:

Concept:

- Lenz's law states that the induced current opposes the change in magnetic flux through a closed circuit.
- A current-carrying straight conductor experiences force $\vec{F} = I\vec{\ell} \times \vec{B}$, where $\vec{\ell}$ points along the conventional current.

Step 1: Find the induced current direction Conductor 1 moves left, increasing the area enclosed by the two conductors and rails. The inward magnetic flux therefore increases. To oppose this increase, the induced current produces an outward field and flows anticlockwise as viewed on the page. It flows upward through conductor 2, along $+\hat{j}$.

Step 2: Apply the magnetic-force rule to conductor 2 The magnetic field points into the page, along $-\hat{k}$ in the displayed coordinate system. For conductor length ℓ ,

$$\vec{F}_2 = I\ell\hat{j} \times (-B\hat{k}) = -I\ell B\hat{i}.$$

The force is in the plane of the page and perpendicular to the vertical conductor. Thus the vertical choices (B) and (D), and the out-of-plane choice (C), cannot represent this force.

Step 3: Conclusion The force on conductor 2 is leftward, along $-\hat{i}$. Hence, the correct option is (A).

Quick Tip to Solve: First use the growing loop area to find the induced current, then apply $\vec{\ell} \times \vec{B}$ specifically to conductor 2.

6. An ac voltage is given as $v = 14 \sin(314t)$ V. The average and the effective value of the voltage (in V) over a cycle are respectively: [1 mark]

- (A) 14 and 7
- (B) 10 and 14
- (C) 0 and 10
- (D) 10 and 0

Correct Answer: (C) 0 and 10

Solution:

Concept:

- For a sinusoidal voltage $v = V_0 \sin \omega t$, the positive and negative half-cycles cancel in the average over a complete cycle.
- The effective voltage is the root-mean-square value: $V_{\text{rms}} = \sqrt{\langle v^2 \rangle} = V_0/\sqrt{2}$.

Step 1: Identify the peak and the full-cycle average Comparing $v = 14 \sin(314t)$ V with the standard expression gives $V_0 = 14$ V. Since the average of a sine function over its full period is zero,

$$V_{\text{avg}} = V_0 \langle \sin \omega t \rangle = 0.$$

This is the signed full-cycle average, not a half-cycle average or an average of the rectified voltage.

Step 2: Calculate the effective voltage Since $\langle \sin^2 \omega t \rangle = 1/2$,

$$V_{\text{rms}} = \frac{14}{\sqrt{2}} \text{ V} \simeq 9.90 \text{ V} \simeq 10 \text{ V}.$$

Options (A) and (B) give a nonzero full-cycle average. Option (D) interchanges the zero average and the nonzero effective value. The angular frequency does not change either result for a complete cycle.

Step 3: Conclusion The average and effective voltages are respectively 0 V and approximately 10 V. Hence, the correct option is (C).

Quick Tip to Solve: For a complete sine-wave cycle, write zero for the signed average and divide the peak voltage by $\sqrt{2}$ for the effective value.

7. The ratio of amplitude of electric field to the amplitude of the magnetic field associated with an electromagnetic wave propagating in glass ($n = 1.5$) is: [1 mark]

- (A) $3 \times 10^8 \text{ m s}^{-1}$
- (B) $2 \times 10^8 \text{ m s}^{-1}$
- (C) $3 \cdot 3 \times 10^{-9} \text{ m s}^{-1}$
- (D) $5 \times 10^{-9} \text{ m s}^{-1}$

Correct Answer: (B) $2 \times 10^8 \text{ m s}^{-1}$

Solution:

Concept:

- For a plane electromagnetic wave, the ratio of electric-field amplitude E_0 to magnetic-field amplitude B_0 equals the wave speed: $E_0/B_0 = v$.
- The refractive index of a medium is $n = c/v$, where $c = 3 \times 10^8 \text{ m s}^{-1}$ is the speed of light in vacuum.

Step 1: Use the speed in glass The stated refractive index is $n = 1.5$. Therefore the electromagnetic wave travels in glass with speed

$$v = \frac{c}{n} = \frac{3 \times 10^8}{1.5} \text{ m s}^{-1} = 2 \times 10^8 \text{ m s}^{-1}.$$

The field-amplitude ratio must use this speed in the medium.

Step 2: Match the ratio and its units Since $E_0 = vB_0$, the required ratio equals the speed calculated above. Option (A) uses the vacuum speed and ignores the glass. The small values in (C) and (D) resemble reciprocal speeds; B_0/E_0 , rather than the asked E_0/B_0 , has inverse-speed dimensions. They cannot represent the requested ratio.

Step 3: Conclusion The amplitude ratio is $\frac{E_0}{B_0} = 2 \times 10^8 \text{ m s}^{-1}$. Hence, the correct option is (B).

Quick Tip to Solve: Remember that E_0/B_0 is the local wave speed; in a medium of refractive index n , use c/n .

8. While studying photoelectric emission from a given surface, the wavelength of the incident radiation is changed from 600 nm to 400 nm, keeping the intensity of radiation the same. Then: [1 mark]

- (A) cut-off potential will decrease.
- (B) cut-off potential will increase.
- (C) saturation current will decrease.
- (D) saturation current will increase.

Correct Answer: (B) cut-off potential will increase.

Solution:

Concept:

- Einstein's photoelectric equation is $eV_0 = h\nu - \phi = hc/\lambda - \phi$, where V_0 is the magnitude of the stopping potential and ϕ is the surface work function.
- Stopping potential measures maximum photoelectron kinetic energy. Saturation current measures the emission rate; these are different observables.

Step 1: Compare photon energies The surface is unchanged, so its work function stays fixed. Reducing the wavelength from 600 nm to 400 nm increases photon energy. Hence the change in maximum kinetic energy is positive:

$$\Delta K_{\max} = hc \left(\frac{1}{400 \text{ nm}} - \frac{1}{600 \text{ nm}} \right) > 0.$$

More energetic photoelectrons require a larger opposing potential to stop them.

Step 2: Assess the proposed changes Option (A) reverses the energy trend. In the usual CBSE comparison, saturation current is controlled by intensity, whereas stopping potential is controlled by frequency. The intensity has not been increased or decreased, so options (C) and (D) are not the stated textbook consequence. More generally, a wavelength dependence of the emission rate would also require information about the surface's photoelectric yield; it does not alter the definite increase of V_0 .

Step 3: Conclusion The magnitude of the cut-off potential increases. Hence, the correct option is (B).

Quick Tip to Solve: For the same emitting surface, compare $1/\lambda$ in $eV_0 = hc/\lambda - \phi$: a shorter wavelength requires a larger stopping potential.

9. Radiation of wavelength 331 nm irradiates the following metals:

Metal	Work Function (eV)
Na	1.92
K	2.15
Ca	3.20
Mo	4.17

Which of the following statements is correct?

[1 mark]

- (A) Only Na and K show photoelectric emission.
- (B) Only Mo will not show photoelectric emission.
- (C) All of the given metals show photoelectric emission.
- (D) None of them show photoelectric emission.

Correct Answer: (B) Only Mo will not show photoelectric emission.

Solution:

Concept:

- Photoelectric emission occurs when the incident photon energy $E = hc/\lambda$ is at least the metal's work function ϕ .
- Use $hc \simeq 1242 \text{ eV nm}$ when wavelength is in nanometres. Any excess $E - \phi$ appears as maximum photoelectron kinetic energy.

Step 1: Calculate the incident photon energy The wavelength is 331 nm. Using the supplied physical constants and expressing energy in electron volts gives

$$E = \frac{(6.63 \times 10^{-34})(3 \times 10^8)}{(331 \times 10^{-9})(1.6 \times 10^{-19})} \text{ eV} \simeq 3.76 \text{ eV}.$$

Step 2: Compare the four work functions This energy exceeds 1.92 eV for Na, 2.15 eV for K and 3.20 eV

for Ca, so all three emit photoelectrons. It is below 4.17 eV for Mo, so Mo does not emit. Option (A) wrongly excludes Ca; option (C) wrongly includes Mo; option (D) wrongly excludes Na, K and Ca.

Step 3: Conclusion Only Mo will not show photoelectric emission. Hence, the correct option is (B).

Quick Tip to Solve: First convert the wavelength to one photon energy, then compare that single value with every work function; intensity cannot overcome an energy below threshold.

10. The kinetic energy of a charged particle is increased to four times of its initial value. The de Broglie wavelength associated with the particle will: [1 mark]

- (A) increase by 100% of its initial value.
- (B) increase by 50% of its initial value.
- (C) decrease by 25% of its initial value.
- (D) decrease by 50% of its initial value.

Correct Answer: (D) decrease by 50% of its initial value.

Solution:

Concept:

- A particle of momentum p has de Broglie wavelength $\lambda = h/p$, where h is Planck's constant.
- For non-relativistic motion, kinetic energy is $K = p^2/(2m)$. Therefore, for the same particle, $\lambda = h/\sqrt{2mK}$, so $\lambda \propto K^{-1/2}$.

Step 1: Find the wavelength ratio The mass stays unchanged while the kinetic energy becomes $K_f = 4K_i$. Applying the inverse-square-root dependence gives

$$\frac{\lambda_f}{\lambda_i} = \sqrt{\frac{K_i}{K_f}} = \frac{1}{2}.$$

Thus doubling the momentum halves the associated wavelength.

Step 2: Calculate the percentage decrease The reduction is measured relative to the initial wavelength:

$$\frac{\lambda_i - \lambda_f}{\lambda_i} \times 100\% = \left(1 - \frac{1}{2}\right) \times 100\% = 50\%.$$

Options (A) and (B) predict an increase even though momentum increases. Option (C) gives the wrong fractional decrease; wavelength depends on the square root of kinetic energy, not directly on kinetic energy.

Step 3: Conclusion The de Broglie wavelength decreases by 50% of its initial value. Hence, the correct option is (D).

Quick Tip to Solve: For an unchanged particle, take the square root of the energy multiplier and invert it: four times the kinetic energy gives half the wavelength.

11. Paschen series in spectrum of hydrogen atom lies in:

[1 mark]

- (A) infrared region
- (B) ultraviolet region
- (C) visible region
- (D) partly in ultraviolet region and partly in visible region

Correct Answer: (A) infrared region

Solution:

Concept:

- A hydrogen spectral series is identified by the final energy level. Paschen transitions terminate at $n_f = 3$, starting from $n_i = 4, 5, 6, \dots$
- The Rydberg formula is $1/\lambda = R_H(1/n_f^2 - 1/n_i^2)$, where $R_H \simeq 1.097 \times 10^7 \text{ m}^{-1}$.

Step 1: Examine the shortest Paschen wavelength For fixed $n_f = 3$, the largest photon energy occurs at the series limit $n_i \rightarrow \infty$. The shortest wavelength is therefore

$$\lambda_{\min} = \frac{9}{R_H} \simeq 8.20 \times 10^{-7} \text{ m} = 820 \text{ nm}.$$

Every other Paschen transition emits a photon of still longer wavelength.

Step 2: Identify the spectral region Even 820 nm is beyond the red end of the visible spectrum. Hence the whole Paschen series lies in the infrared. Ultraviolet radiation in option (B) is associated with the Lyman series; the familiar visible hydrogen lines are Balmer lines. Since no Paschen line is visible or ultraviolet, options (C) and (D) also fail.

Step 3: Conclusion The Paschen series lies in the infrared region. Hence, the correct option is (A).

Quick Tip to Solve: Recall the terminating levels: Lyman ends at 1, Balmer at 2, and Paschen at 3; Paschen and the higher series are infrared.

12. In a reversed-biased p-n junction diode, the applied voltage mostly drops across:

[1 mark]

- (A) p-region only
- (B) n-region only
- (C) depletion region
- (D) the diode

Correct Answer: (C) depletion region

Solution:

Concept:

- The depletion layer of a p-n junction contains immobile ionised donor and acceptor atoms but very few mobile majority carriers.
- Reverse bias increases the junction potential barrier and widens the depletion region. The relatively conducting neutral p and n regions have much smaller voltage drops.

Step 1: Locate the region that supports the field Under reverse bias, the p side is connected to the negative terminal and the n side to the positive terminal. Majority carriers are pulled away from the junction. The widened region depleted of mobile carriers supports a strong electric field and the

additional barrier potential.

Step 2: Compare the possible voltage-drop locations Only a small reverse current flows before breakdown, so voltage drops in the conducting neutral p and n regions are small. Most of the applied reverse voltage appears across the depletion region. Options (A) and (B) incorrectly assign it to a neutral region alone. Option (D) names the whole component and does not identify where within it the drop is concentrated.

Step 3: Conclusion The applied reverse voltage mostly drops across the depletion region. Hence, the correct option is (C).

Quick Tip to Solve: In reverse bias, identify the carrier-poor region: it widens and supports almost all the applied voltage, while the neutral regions remain relatively conducting.

13. Questions number 13 to 16 are Assertion (A) and Reason (R) type questions. Two statements are given — one labelled Assertion (A) and the other labelled Reason (R). Select the correct answer from the codes (A), (B), (C) and (D) as given below.

Assertion (A): The work done, in taking a unit charge around a closed loop of an electric circuit involving cells and resistors in the loop, is zero.

Reason (R): The potential at a point depends on the location of the point in the loop. After completing one round, the charge comes back to the point of start. [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:

- Electric potential is single-valued at each point of a steady circuit. After returning to the starting point, the net potential change is zero.
- Kirchhoff's loop rule expresses energy conservation: the algebraic sum of potential rises across cells and potential drops across resistors around a closed loop is zero, $\sum \Delta V = 0$.

Step 1: Evaluate the Assertion A unit charge returns to its initial position after one circuit of a closed loop. The algebraic net work per unit charge associated with all potential changes is zero:

$$\frac{W_{\text{net}}}{q} = \sum \Delta V = 0.$$

Energy supplied by the cells balances energy dissipated in the resistors; zero net work does not mean that no energy is dissipated. Assertion (A) is true.

Step 2: Evaluate the Reason Different points of the loop can have different potentials, but the potential at a given point is well-defined. Completing a full round brings the charge back to exactly its starting potential. Reason (R) is therefore true.

Step 3: Test the explanatory link Returning to the same potential makes the net potential difference zero and hence makes the algebraic net work for a unit charge zero. The Reason directly explains the Assertion. Option (B) misses this link, while (C) and (D) incorrectly declare one or both statements false.

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

Quick Tip to Solve: For a closed circuit loop, add potential rises and drops with signs: returning to the same point fixes their sum at zero even while resistors dissipate energy.

14. Assertion (A): When a ferromagnetic substance is heated to high temperature it becomes paramagnetic in nature.

Reason (R): The disappearance of magnetisation of a ferromagnet is abrupt and not gradual. [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:

- Ferromagnetism depends on the cooperative alignment of atomic magnetic moments. Thermal agitation increasingly disrupts this alignment as temperature rises.
- Above its characteristic Curie temperature T_C , a ferromagnetic material behaves as a paramagnet and no longer has spontaneous ferromagnetic magnetisation.

Step 1: Evaluate the Assertion Heating a ferromagnetic substance sufficiently, beyond its Curie temperature, destroys its spontaneous ordered alignment. Its moments can still respond weakly to an applied magnetic field, so the material becomes paramagnetic. Assertion (A) is true.

Step 2: Evaluate the Reason In the standard temperature dependence of a ferromagnet, spontaneous magnetisation decreases gradually as thermal agitation increases and tends to zero at the Curie temperature. It does not retain its initial value and then disappear abruptly. Therefore the claim that its disappearance is abrupt and not gradual is false.

Step 3: Choose the matching code A true Assertion and a false Reason match code (C). Options (A) and (B) require a true Reason, which is not the case. Option (D) incorrectly denies the well-established transition to paramagnetic behaviour at high temperature.

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

Quick Tip to Solve: Distinguish the named transition temperature from the magnetisation curve: spontaneous magnetisation decreases on heating and vanishes at the Curie point.

15. Assertion (A): When a convex lens made of glass is immersed in water, its converging power increases.

Reason (R): The focal length of a lens depends only on the radii of curvature of its two faces. [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:

- For a thin lens in a medium, the lens-maker relation is $P = 1/f = (n_g/n_m - 1)(1/R_1 - 1/R_2)$, where n_g and n_m are the refractive indices of glass and the surrounding medium.
- Converging power decreases when the positive refractive-index contrast decreases, even though the radii R_1 and R_2 are unchanged.

Step 1: Evaluate the assertion Water has a greater refractive index than air but a smaller refractive index than ordinary glass. On immersing the lens, $n_g/n_m - 1$ decreases. The convex lens therefore has a longer focal length and a smaller positive power. Assertion (A), which says the power increases, is false.

Step 2: Evaluate the reason The lens-maker relation contains both the radii of curvature and the refractive index of the lens relative to its surroundings. Thus the focal length does not depend only on the radii. Reason (R) is false.

Step 3: Match the assertion-reason code Since both statements are false, the reason cannot explain the assertion. Options (A) and (B) require both statements to be true, while option (C) requires a true assertion; 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: Keep the lens shape fixed and compare $n_g/n_m - 1$: a smaller positive value means weaker convergence and a longer focal length.

16. Assertion (A): The conductivity of an n-type semiconductor is higher than that of a p-type semiconductor at a given temperature.

Reason (R): The electrons being in the conduction band in n-type semiconductor are more mobile than the holes in the valence band in p-type semiconductor. [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:

- Semiconductor conductivity is $\sigma = e(n\mu_e + p\mu_h)$, where n, p are electron and hole concentrations and μ_e, μ_h are their mobilities.
- In the usual comparison of the same semiconductor at equal doping concentration and temperature, electrons have greater mobility than holes: $\mu_e > \mu_h$.

Step 1: Evaluate the assertion For the standard comparison with equal majority-carrier concentrations N , conduction is mainly by electrons in the n-type specimen and by holes in the p-type specimen. Neglecting the small minority-carrier contribution gives

$$\sigma_n \simeq eN\mu_e, \quad \sigma_p \simeq eN\mu_h.$$

Since $\mu_e > \mu_h$, the n-type specimen has higher conductivity. The assertion is true in this intended comparison. If doping concentrations differed arbitrarily, temperature alone would not guarantee this ordering.

Step 2: Evaluate the reason Electrons in the conduction band have greater mobility than holes in the valence band of the same semiconductor under comparable conditions. Thus the reason correctly states the relevant carrier property and is true.

Step 3: Check whether the reason explains the assertion At equal carrier concentration, conductivity is directly proportional to mobility. The higher electron mobility therefore explains the greater n-type conductivity. The code for two true statements with a correct explanation applies; the alternatives denying the explanation or declaring either statement false do not.

Step 4: Conclusion Under the usual equal-doping comparison, both statements are true and the reason correctly explains the assertion. Hence, the correct option is (A).

Quick Tip to Solve: Compare $\sigma \simeq eN\mu$ at equal carrier density: the carrier with greater mobility produces greater conductivity.

Section B (10 marks)

17. An electric dipole consists of two point charges $+1\ \mu\text{C}$ and $-1\ \mu\text{C}$, held 10 cm apart. It is subjected to a uniform electric field of 100 N/C. Calculate the amount of work done in turning the dipole from its position of stable equilibrium to the position of unstable equilibrium, in the field. [2 marks]

Solution:

Concept:

- An electric dipole has moment $p = qd$, where q is the magnitude of either charge and d is the full separation between the charges.
- In a uniform field E , its potential energy is $U = -pE \cos \theta$. Stable equilibrium is at $\theta = 0$ and unstable equilibrium at $\theta = \pi$.
- Work supplied by an external agent in a slow rotation equals the increase in potential energy: $W_{\text{ext}} = U_f - U_i$.

Step 1: Convert the separation and find the dipole moment The stated distance is the full charge separation, so it is used directly. With $q = 1 \times 10^{-6}\text{ C}$ and $d = 10\text{ cm} = 0.10\text{ m}$,

$$p = qd = (1 \times 10^{-6})(0.10) = 1.0 \times 10^{-7}\text{ C m}.$$

Step 2: Find the energy increase during the rotation Initially the dipole moment is parallel to the field, giving the minimum energy $U_i = -pE$. Finally it is antiparallel to the field, giving the maximum energy $U_f = +pE$. Therefore,

$$\begin{aligned} W_{\text{ext}} &= pE - (-pE) = 2pE, \\ &= 2(1.0 \times 10^{-7})(100) \\ &= 2.0 \times 10^{-5}\text{ J}. \end{aligned}$$

The positive sign indicates that energy must be supplied against the restoring torque. The electric field itself does the opposite work, $-2.0 \times 10^{-5}\text{ J}$.

Step 3: Conclusion The work required to turn the dipole from stable to unstable equilibrium is $2.0 \times 10^{-5}\text{ J}$, or $20\ \mu\text{J}$.

Quick Tip to Solve: For a half-turn from parallel to antiparallel, use $W = 2pE$; use the full charge separation when calculating $p = qd$.

18(a). State Huygens principle. How did Huygens justify the absence of the backwave on a spherical wavefront? [2 marks]

Solution:

Concept:

- A wavefront is a surface joining points that have the same phase. Huygens' construction finds its position after a short time using secondary wavelets.
- In a homogeneous medium, a secondary wavelet spreads with the wave speed v and has radius $v\Delta t$ after a time interval Δt .

Step 1: State Huygens' principle Every point on a wavefront acts as a source of secondary spherical wavelets that spread through the medium with the speed of the wave. The forward envelope, or

common tangent surface, of these wavelets at a later instant gives the new wavefront. For an outward-moving spherical wavefront, this envelope is a larger concentric sphere.

Step 2: Explain the exclusion of the backwave If all directions were given equal amplitude, the geometrical construction would also allow a backward envelope. Huygens excluded this by assuming that secondary-wavelet amplitude is greatest in the forward direction and zero in the backward direction. Hence no backward-propagating wavefront results. This directional-amplitude assumption is additional to the simple geometrical construction; the existence of a backward envelope alone does not mean a physical backwave is present.

Step 3: Conclusion The new wavefront is the forward envelope of secondary wavelets. The backwave is absent because the secondary-wavelet amplitude is assumed to vanish in the backward direction.

Quick Tip to Solve: State both parts of the principle: secondary sources and their forward envelope. For the backwave, explicitly state that backward amplitude is zero.

OR

18(b). In a single-slit diffraction experiment, light of wavelength λ illuminates the slit of width 'a'. The diffraction pattern is observed on a screen kept at a distance D from the slits.

(i) Depict variation of intensity in the fringe pattern with the angular position of the fringes.

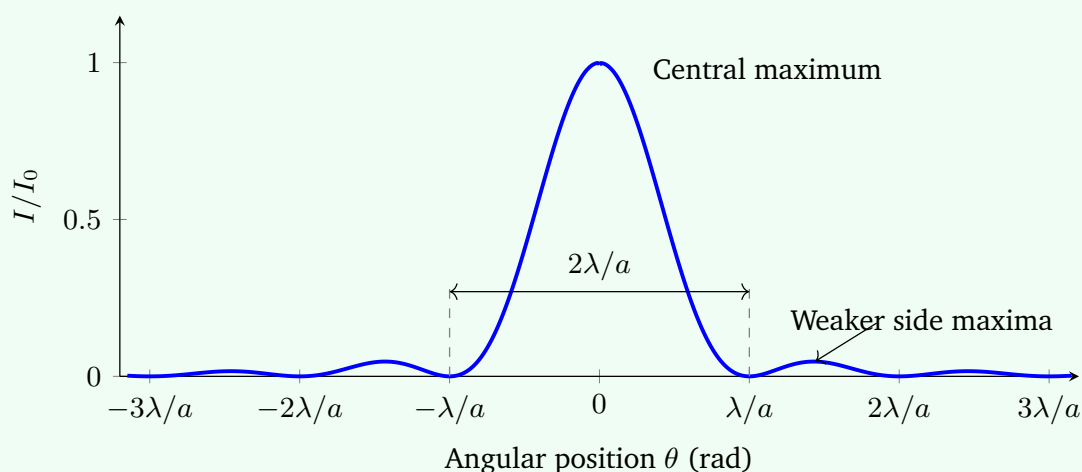
(ii) How is the linear width of central maximum affected when separation between the slit and the screen is decreased? [2 marks]

Solution:

Concept:

- For a single slit of width a , the diffraction intensity is $I = I_0(\sin \beta / \beta)^2$, where $\beta = \pi a \sin \theta / \lambda$, θ is the angle from the central axis and I_0 is the central intensity.
- The minima satisfy $a \sin \theta = m\lambda$, with $m = \pm 1, \pm 2, \dots$. For small angles, the first minima occur at $\theta \simeq \pm \lambda / a$.

Step 1: Depict intensity against angular position The pattern is symmetric about $\theta = 0$, where the central maximum is brightest. It is bounded by the first minima at $\theta \simeq \pm \lambda / a$. Weaker secondary maxima occur on both sides, with successively decreasing peak intensities. The central maximum has angular width $2\lambda / a$, twice the spacing between adjacent minima on either side. The graph uses the small-angle approximation, with intensity normalized to I_0 .



Single-slit diffraction intensity against angular position (small angles).

Step 2: Find how screen separation affects the central width At screen distance D , a first minimum is at $y_1 = D \tan \theta_1 \simeq D\lambda/a$. The linear width between the two first minima is therefore

$$w = 2y_1 = \frac{2D\lambda}{a}.$$

With a and λ fixed, the width is directly proportional to D . Thus moving the screen closer decreases the linear width in the same ratio: $w'/w = D'/D$. The angular width is unchanged within the far-field, small-angle approximation.

Step 3: Conclusion The pattern has a broad, bright central peak and weaker side peaks. Decreasing the slit-screen separation decreases the central maximum's linear width, since $w = 2D\lambda/a$.

Quick Tip to Solve: Locate the two first minima at $\pm D\lambda/a$, then subtract their positions; the factor of two belongs to the full central width.

19. A small bulb is placed at the bottom of a tank, containing a transparent liquid of refractive index $\sqrt{2}$, to a depth of 1 m. Calculate the area of the surface of the liquid through which light from the bulb emerges. [2 marks]

Solution:

Concept:

- At a liquid–air boundary, a ray can emerge when its angle of incidence is less than the critical angle C , where $\sin C = n_{\text{air}}/n_{\text{liquid}}$.
- Rays from a point source at depth h strike the surface at radius $r = h \tan i$, where i is measured from the normal. Rotational symmetry makes the emergence region a circular disc.

Step 1: Calculate the critical angle Taking the refractive index of air as unity and using the given liquid index $\sqrt{2}$,

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

Rays incident at larger angles undergo total internal reflection and cannot emerge into the air. The critical ray defines the limiting edge of the illuminated surface region.

Step 2: Determine the radius and surface area The perpendicular from the bulb to the surface is the

axis of the cone of escaping rays. In its axial cross-section, the source depth and limiting radius form a right triangle. With $h = 1$ m,

$$r = h \tan C = (1 \text{ m}) \tan 45^\circ = 1 \text{ m}.$$

The requested area is the planar surface disc, so

$$A = \pi r^2 = \pi (1 \text{ m})^2 = \pi \text{ m}^2.$$

Step 3: Conclusion Light emerges through a circular surface region of area $\pi \text{ m}^2 \approx 3.14 \text{ m}^2$, centred directly above the bulb.

Quick Tip to Solve: First find the critical angle, then use $r = h \tan C$; the emergence area is πr^2 , not the curved area of the cone.

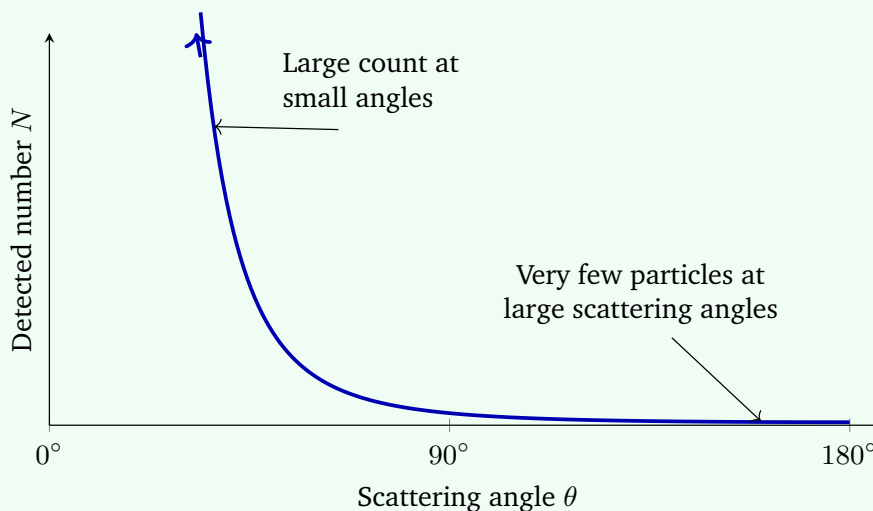
20. Draw the graph showing the variation of number of scattered alpha particles (N) detected with scattering angle (θ) in Geiger-Marsden experiment. Infer two conclusions from the graph. [2 marks]

Solution:

Concept:

- In the Geiger–Marsden experiment, positively charged alpha particles scatter through electrostatic repulsion from the atom’s concentrated positive charge.
- For fixed incident energy, foil thickness and detector geometry, Rutherford scattering gives $N \propto 1/\sin^4(\theta/2)$. Here N is the number detected in a fixed solid angle and θ is the scattering angle.

Step 1: Plot the scattering distribution Put the scattering angle θ on the horizontal axis and the detected number N on the vertical axis. The count is very large at small angles, falls rapidly as the angle increases, and remains very small but nonzero near 180° . The curve below uses a relative vertical scale; its upper continuation indicates the much larger count towards the forward direction.



Detected alpha-particle count versus scattering angle; relative vertical scale.

Step 2: Infer the atomic structure First conclusion: Most alpha particles pass through the foil with little or no deflection, so most of the volume of an atom is empty space.

Second conclusion: Very few particles suffer large deflections or turn back. Such strong deflections

show that the atom's positive charge and almost all its mass are concentrated in a very small, dense central nucleus. Their rarity shows how small the nucleus is compared with the atom.

Step 3: Conclusion The graph falls steeply from a high forward-scattering count to a very small large-angle count. It supports a mostly empty atom containing a tiny, dense, positively charged nucleus.

Quick Tip to Solve: Link the high small-angle count to empty space, and the rare large-angle or backward events to the small, massive positive nucleus.

21. The hole concentration in an intrinsic semiconductor is $5 \times 10^8 \text{ m}^{-3}$. When it is doped with certain impurity, the electron concentration becomes $4 \times 10^{12} \text{ m}^{-3}$. Find the new value of the hole concentration. Also identify the type of new semiconductor formed after doping. [2 marks]

Solution:

Concept:

- In an intrinsic semiconductor, the equilibrium electron and hole concentrations are equal: $n_e = n_h = n_i$, where n_i is the intrinsic carrier concentration.
- At a fixed temperature, the mass-action relation is $n_e n_h = n_i^2$. Doping changes the individual carrier concentrations while their equilibrium product remains fixed.

Step 1: Determine the intrinsic carrier product The original sample is intrinsic, so its stated hole concentration is also its intrinsic concentration:

$$n_i = 5 \times 10^8 \text{ m}^{-3}.$$

Consequently, at the same temperature the product required after doping is

$$n_i^2 = (5 \times 10^8)^2 = 25 \times 10^{16} \text{ m}^{-6}.$$

Step 2: Calculate the new hole concentration and identify the majority carrier The doped electron concentration is $n_e = 4 \times 10^{12} \text{ m}^{-3}$. Substituting into the mass-action relation gives

$$\begin{aligned} n_h &= \frac{n_i^2}{n_e} = \frac{25 \times 10^{16}}{4 \times 10^{12}} \text{ m}^{-3} \\ &= 6.25 \times 10^4 \text{ m}^{-3}. \end{aligned}$$

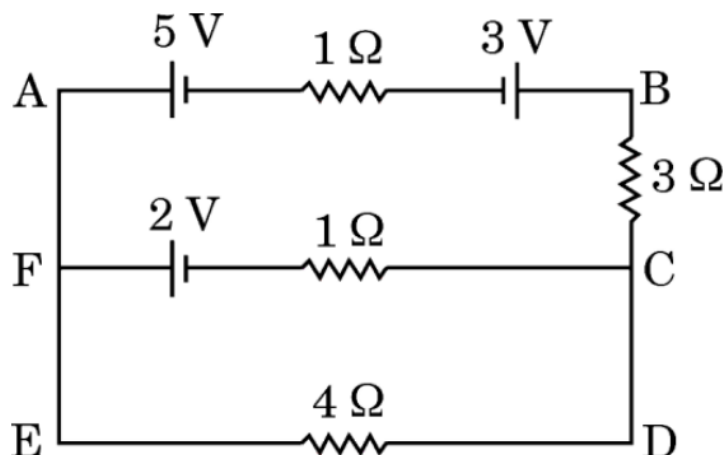
The electron concentration is now far greater than the hole concentration. Thus electrons are the majority carriers and holes are the minority carriers, identifying donor-type doping and an n-type semiconductor.

Step 3: Conclusion The new hole concentration is $6.25 \times 10^4 \text{ m}^{-3}$, and the doped sample is an n-type semiconductor.

Quick Tip to Solve: Square the intrinsic concentration before dividing by the doped electron concentration; identify the type from the majority carrier.

Section C (21 marks)

22. State Kirchhoff's rules. Using these rules, find the current flowing through branch FC in the given circuit. [3 marks]



Solution:

Concept:

- Kirchhoff's junction rule: the algebraic sum of currents at any junction is zero, or total current entering equals total current leaving. This follows from conservation of charge.
- Kirchhoff's loop rule: the algebraic sum of potential changes around any closed loop is zero, $\sum \Delta V = 0$. This follows from conservation of energy; crossing a cell from its negative to positive terminal gives a rise in potential.

Step 1: Assign branch currents and read the cell polarities The ideal wires make A, F, E one node and C, D another. Let $V = V_F - V_C$. Define signed currents I_t, I_m, I_b from the left node to the right node through the top path ABC , middle branch FC , and bottom path ED , respectively.

On the top path, the 5V cell causes a potential drop and the oppositely oriented 3V cell a rise. Their net drop is 2V; the series resistance is $1 + 3 = 4\Omega$. The middle cell also causes a 2V drop from F towards C .

Step 2: Apply the loop and junction rules The potential difference between the two nodes is the same along all three paths. The loop rule therefore gives

$$V = 2\text{V} + (4\Omega)I_t,$$

$$V = 2\text{V} + (1\Omega)I_m,$$

$$V = (4\Omega)I_b.$$

There is no external current supply to either node. Since all three currents were defined as leaving the left node, the junction rule requires

$$I_t + I_m + I_b = 0.$$

A negative current will simply mean that the actual direction is opposite to our chosen reference direction.

Step 3: Solve for the current in the middle branch Substitute the three branch-current expressions

into the junction equation:

$$\frac{V - 2V}{4\Omega} + \frac{V - 2V}{1\Omega} + \frac{V}{4\Omega} = 0.$$

Multiplying by 4Ω gives $6V - 10V = 0$, and hence $V = 5/3\text{ V}$. Thus

$$I_m = \frac{(5/3 - 2)V}{1\Omega} = -\frac{1}{3}\text{ A}.$$

As a check, $I_t = -1/12\text{ A}$ and $I_b = 5/12\text{ A}$, whose sum with I_m is zero. The negative middle current is directed from C to F .

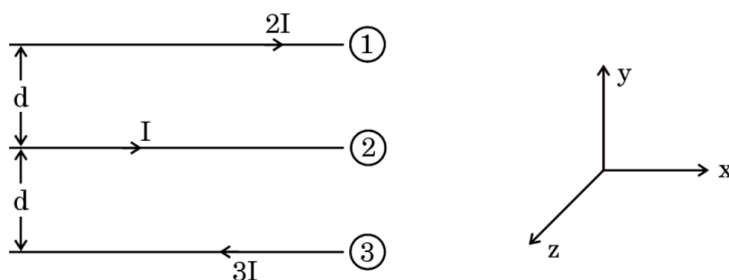
Step 4: Conclusion The current through branch FC has magnitude $1/3\text{ A} \approx 0.33\text{ A}$ and flows $C \rightarrow F$.

Quick Tip to Solve: Read the long plate of each cell as positive before writing loop equations. Keep an assumed direction and let a negative result identify the actual current direction.

23(a). The figure given below shows three straight long parallel conductors (1), (2) and (3) kept in x - y plane, carrying currents $2I$, I and $3I$ respectively as shown in figure.

Find the magnitude and direction of:

- net magnetic field at a point on conductor (1) and
- net magnetic force acting on unit length of conductor (1), due to conductors (2) and (3). [3 marks]



Solution:

Concept:

- A long straight conductor carrying current i produces a field of magnitude $B = \mu_0 i / (2\pi r)$ at perpendicular distance r . Its direction follows the right-hand thumb rule.
- Fields superpose vectorially. The force per unit length on a conductor is $\vec{F}/L = i\hat{\ell} \times \vec{B}_{\text{ext}}$, where $\hat{\ell}$ points along its current and only the external field is included.

Step 1: Find the fields at conductor (1) Conductor (1) is at a distance d above conductor (2) and $2d$ above conductor (3). Take the axes exactly as drawn. Current in (2) flows along $+x$, so its field at (1) is along $+z$; current in (3) flows along $-x$, so its field there is along $-z$.

$$\vec{B}_2 = \frac{\mu_0 I}{2\pi d} \hat{z}, \quad \vec{B}_3 = -\frac{3\mu_0 I}{4\pi d} \hat{z}.$$

Thus the field from (3) is larger, even though (3) is farther away, because its current is three times as large.

Step 2: Add the fields and calculate the force Adding the two opposite fields gives

$$\vec{B}_{\text{net}} = \left(\frac{\mu_0 I}{2\pi d} - \frac{3\mu_0 I}{4\pi d} \right) \hat{z} = -\frac{\mu_0 I}{4\pi d} \hat{z}.$$

Current in conductor (1) is $2I$ along $+x$. Since $\hat{x} \times \hat{z} = -\hat{y}$,

$$\frac{\vec{F}_1}{L} = 2I\hat{x} \times \left(-\frac{\mu_0 I}{4\pi d} \hat{z} \right) = \frac{\mu_0 I^2}{2\pi d} \hat{y}.$$

As a direction check, (2) attracts (1) downward, while (3) repels (1) upward. The upward repulsion is larger, agreeing with the cross-product result.

Step 3: Conclusion (i) The net field has magnitude $\mu_0 I/(4\pi d)$, directed along the negative z -axis. (ii) The force per unit length has magnitude $\mu_0 I^2/(2\pi d)$, directed along the positive y -axis. With SI inputs, these are in tesla and N m^{-1} , respectively.

Quick Tip to Solve: Compare current divided by distance first: the opposing field contributions are proportional to I/d and $3I/(2d)$. Use the larger contribution to fix the net field direction.

OR

23(b). A rectangular loop of sides l and b and resistance 'R' is kept in a region in which the magnetic field varies as $B = B_0 \sin \omega t$.

(i) Derive expression for the emf induced in the loop.

(ii) Find the effective value of current that flows in the loop.

[3 marks]

Solution:

Concept:

- Magnetic flux through a loop is $\Phi = BA \cos \theta$, where A is its area and θ is the angle between the field and the area normal. Faraday's law for one turn is $\varepsilon = -d\Phi/dt$.
- For a resistive loop, $i = \varepsilon/R$. The effective or root-mean-square current is $I_{\text{rms}} = \sqrt{\langle i^2 \rangle}$; for a sinusoidal current of peak value I_0 , it equals $I_0/\sqrt{2}$.

Step 1: Differentiate the flux through the loop The loop has area $A = lb$. Taking the specified field to be normal to its plane, and the positive area normal along the positive field direction, the linked flux is

$$\Phi(t) = B_0 lb \sin \omega t.$$

Faraday's law therefore gives

$$\varepsilon(t) = -\frac{d}{dt}(B_0 lb \sin \omega t) = -B_0 lb \omega \cos \omega t.$$

Its peak magnitude is $\varepsilon_0 = B_0 lb \omega$. The minus sign specifies the induced sense relative to the chosen normal and expresses Lenz's law: the induced current opposes the change in flux.

Step 2: Calculate the effective current Neglecting self-inductance, the instantaneous current in the loop of resistance R is

$$i(t) = -\frac{B_0 lb \omega}{R} \cos \omega t.$$

Squaring and averaging over a complete cycle uses $\langle \cos^2 \omega t \rangle = 1/2$. Hence

$$I_{\text{rms}} = \sqrt{\frac{B_0^2 l^2 b^2 \omega^2}{R^2} \frac{1}{2}} = \frac{B_0 l b \omega}{\sqrt{2} R}.$$

This is the steady current that would produce the same average heating in R ; the mean current over a cycle is zero and is not the effective current. The printed statement does not specify the loop orientation. The usual result above assumes a perpendicular field. If a fixed angle θ with the area normal is intended, multiply the emf by $\cos \theta$ and the rms current by $|\cos \theta|$.

Step 3: Conclusion For a field perpendicular to the loop,

$$\boxed{\varepsilon(t) = -B_0 l b \omega \cos \omega t}, \quad \boxed{I_{\text{rms}} = \frac{B_0 l b \omega}{\sqrt{2} R}}.$$

With SI inputs the emf is in volts and the effective current is in amperes.

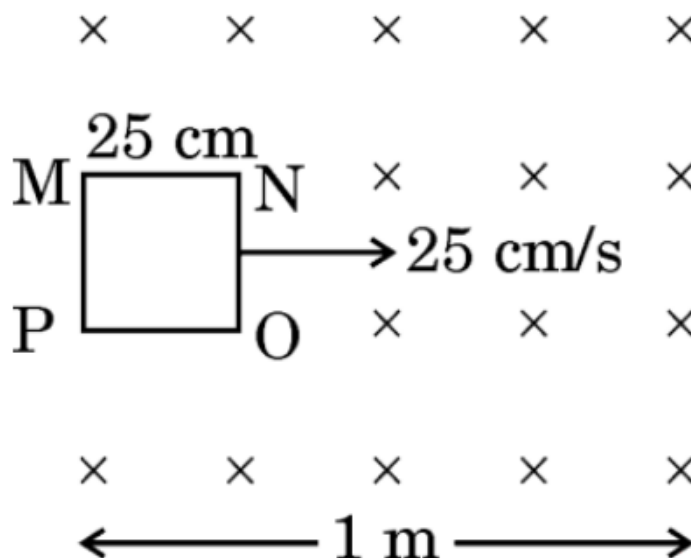
Quick Tip to Solve: Differentiate the given sine field first, so the emf is a cosine with an extra factor ω . Divide its peak by $R\sqrt{2}$ to obtain the effective current.

24. The figure given below shows a square-shaped loop MNOP of side 25 cm placed horizontally in a uniform magnetic field $\vec{B}$ directed vertically downward. The position of the loop at $t = 0$ s is as shown in figure. The loop is pulled with a constant velocity of 25 cm/s till it goes out of the field.

(a) What will be the direction of the induced current in the loop as it goes out of the field? For how long would the current in the loop persist?

(b) Plot graphs showing the variation of magnetic flux and magnitude of induced emf as a function of time.

[3 marks]



Solution:

Concept:

- Magnetic flux is $\Phi = BA_{\text{in}}$, taking the downward area normal as positive, where A_{in} is the loop area still inside the uniform field. Faraday's law gives $|\varepsilon| = |d\Phi/dt|$.
- Lenz's law requires the induced current to oppose a change in flux. While a side of length a leaves

the field at speed v , the area decreases at rate av , so $|\varepsilon| = Bav$.

Step 1: Identify when the loop begins and finishes leaving The diagram shows a field region of width 1 m, with the left side MP initially at its left boundary. The loop side and its speed are

$$a = 0.25 \text{ m}, \quad v = 0.25 \text{ m s}^{-1}.$$

Initially the whole loop lies in the field. Its leading side NO must travel $1 - 0.25 = 0.75$ m to reach the right boundary; its trailing side MP must travel 1 m to leave. Therefore

$$t_1 = \frac{0.75}{0.25} = 3 \text{ s}, \quad t_2 = \frac{1}{0.25} = 4 \text{ s}.$$

Flux is constant until 3 s, decreases between 3 and 4 s, and is zero thereafter. Thus the induced current persists for $t_2 - t_1 = 1$ s, only during the exit interval.

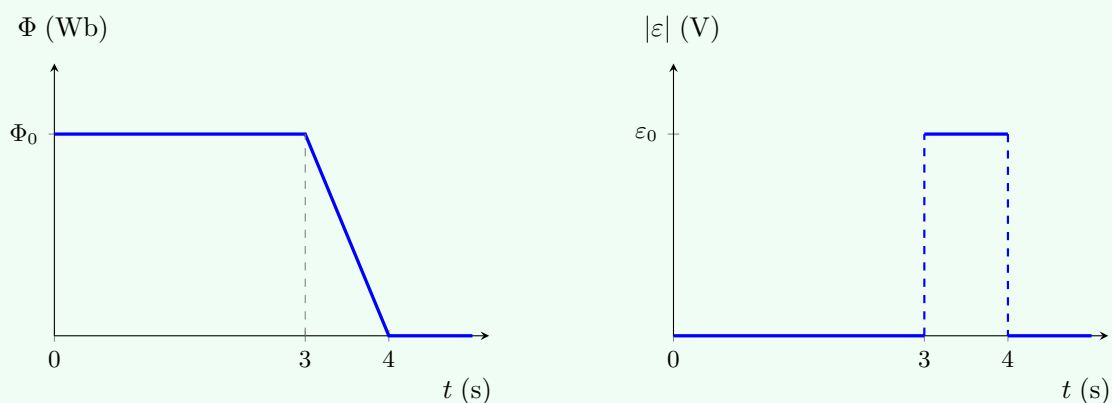
Step 2: Apply Lenz's law to determine the current direction As the loop leaves, downward magnetic flux decreases. The induced current must produce a downward field to oppose that decrease. By the right-hand rule the current is clockwise as viewed from above: $M \rightarrow N \rightarrow O \rightarrow P \rightarrow M$. Before the loop begins leaving, motion within a uniform field does not change its flux, so there is no net induced current.

Step 3: Obtain and plot the flux and emf Write $\Phi_0 = Ba^2$ and $\varepsilon_0 = Bav$. For B in tesla, these are numerically $B/16$ in webers and $B/16$ in volts, respectively. During exit the remaining width decreases linearly from a to zero. Hence

$$\Phi(t) = \begin{cases} \Phi_0, & 0 \leq t \leq 3 \text{ s}, \\ \Phi_0 \frac{4s-t}{1s}, & 3 \text{ s} < t < 4 \text{ s}, \\ 0, & t \geq 4 \text{ s}, \end{cases}$$

$$|\varepsilon(t)| = \begin{cases} 0, & 0 \leq t < 3 \text{ s}, \\ \varepsilon_0, & 3 \text{ s} < t < 4 \text{ s}, \\ 0, & t > 4 \text{ s}. \end{cases}$$

The ideal sharp field boundary gives sudden jumps in the emf at 3 and 4 s. The vertical dashed lines on its graph indicate these jumps. Reversing the chosen area normal would reverse the flux sign, but would leave the emf magnitude and physical current direction unchanged.



Flux and induced emf magnitude, with $\Phi_0 = Ba^2$ and $\varepsilon_0 = Bav$; $a = 0.25 \text{ m}$, $v = 0.25 \text{ m s}^{-1}$.

Step 4: Conclusion The current is clockwise, $M \rightarrow N \rightarrow O \rightarrow P \rightarrow M$, and flows for 1 s , from $t = 3\text{ s}$ to $t = 4\text{ s}$. Flux stays at Ba^2 , then falls linearly to zero; the emf magnitude is a rectangular pulse of height Bav during that same exit interval.

Quick Tip to Solve: Track the leading and trailing sides separately. Their travel distances are 0.75 m and 1 m ; the current starts at 3 s , not at the start of motion.

25. What are infrared waves? Why are these waves referred to as ‘heat waves’? Give any two uses of these waves. [3 marks]

Solution:

Concept:

- Infrared radiation is electromagnetic radiation with wavelengths longer than visible red light, approximately from 700 nm to 1 mm .
- Electromagnetic radiation transfers energy. Absorption of infrared radiation increases the internal energy of a body and commonly raises its temperature.

Step 1: Define infrared waves Infrared waves form the invisible part of the electromagnetic spectrum immediately beyond its red end, between visible light and microwaves. They are transverse electromagnetic waves and travel through vacuum at the speed of light. Hot bodies and vibrating molecules are common sources of infrared radiation; the human body also emits it.

Step 2: Explain the name heat waves Infrared radiation is readily absorbed by many substances, including water molecules present in ordinary materials and tissues. Its absorption increases molecular vibrational and other internal motion. The resulting rise in internal energy produces a heating effect, so infrared waves are commonly called heat waves. This name describes their prominent thermal effect; infrared radiation itself remains an electromagnetic wave.

Step 3: Give two practical uses (i) **Infrared heating and physiotherapy:** infrared lamps provide local warming of body tissues, using the heating effect of absorbed radiation.

(ii) **Remote controls:** television and other appliance remotes send coded infrared pulses to a receiver. The receiver detects the pulses and interprets them as instructions, such as changing the channel or volume.

Step 4: Conclusion Infrared waves are invisible electromagnetic waves beyond the red end of the visible spectrum. Their absorption produces heating, hence the name heat waves. Two uses are infrared heating in physiotherapy and signal transmission in remote controls.

Quick Tip to Solve: Connect the name heat waves to absorption and increased internal energy, then name two distinct applications such as heating lamps and remote controls.

26. (a) Explain how the dual aspect of matter is evident in the de Broglie relation.

(b) Radiation of wavelength λ is incident on a photosensitive surface. Find the de Broglie wavelength of electrons emitted from the surface. Assume that the work function of the surface is negligible.

[3 marks]

Solution:

Concept:

- The de Broglie relation is $\lambda_{dB} = h/p$, where λ_{dB} is the matter wavelength, h is Planck's constant and p is the particle momentum.
- Einstein's photoelectric equation is $K_{\max} = h\nu - \phi$, where $\nu = c/\lambda$, ϕ is the work function and λ is the incident radiation wavelength.
- For a non-relativistic electron of mass m_e , kinetic energy and momentum obey $K = p^2/(2m_e)$.

Step 1: Relate the wave and particle aspects in part (a) Wavelength characterises a wave, whereas momentum characterises a particle. The relation $\lambda_{dB} = h/p$ connects these two descriptions of the same moving material particle. An electron has particle momentum and an associated wavelength that determines its diffraction behaviour. Thus the relation expresses matter's dual nature; increasing momentum decreases its wavelength.

Step 2: Obtain the photoelectron energy in part (b) Each incident photon has energy hc/λ . Neglecting the work function in Einstein's equation gives

$$K_{\max} = \frac{hc}{\lambda} - \phi \simeq \frac{hc}{\lambda}.$$

For electrons emitted without additional energy loss, use this energy to find their momentum:

$$p = \sqrt{2m_e K_{\max}} = \sqrt{\frac{2m_e hc}{\lambda}}.$$

Step 3: Substitute the momentum into the de Broglie relation The electron wavelength is obtained by dividing Planck's constant by its momentum:

$$\lambda_e = \frac{h}{\sqrt{2m_e hc/\lambda}} = \sqrt{\frac{h\lambda}{2m_e c}}.$$

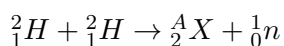
Here λ is the incident wavelength and λ_e is the electron wavelength. In an emitted energy distribution this result is the minimum wavelength, corresponding to the most energetic electrons.

Step 4: Conclusion (a) The de Broglie relation links the wave property wavelength with the particle property momentum, exhibiting matter's dual nature.

(b) For negligible work function, the required photoelectron wavelength is $\lambda_e = \sqrt{h\lambda/(2m_e c)}$.

Quick Tip to Solve: First turn photon wavelength into energy using hc/λ , then find electron momentum using $\sqrt{2m_e K}$; only then use h/p .

27. In the nuclear reaction:



(a) Find the value of A.

(b) Calculate the amount of energy released in the reaction.

Given: $m({}^2_1\text{H}) = 2.014102 \text{ u}$, $m({}^A_2\text{X}) = 3.016049 \text{ u}$, $m({}^1_0\text{n}) = 1.008665 \text{ u}$, $1 \text{ u} = 931.5 \text{ MeV}/c^2$ [3 marks]

Solution:

Concept:

- A nuclear reaction conserves total mass number (nucleon number) and total atomic number (charge number).
- The energy released is the reaction Q -value: $Q = (m_{\text{initial}} - m_{\text{final}})c^2$. A positive mass defect gives a positive energy release.
- With masses in atomic mass units, use $1 \text{ u } c^2 = 931.5 \text{ MeV}$, as supplied in the question.

Step 1: Conserve nucleon number to find A in part (a) The two deuterium nuclei on the left each have mass number 2. The products have mass numbers A and 1, so

$$2 + 2 = A + 1 \Rightarrow A = 3.$$

Charge number is also conserved: $1 + 1 = 2 + 0$. Therefore X , with atomic number 2 and mass number 3, is helium-3, ${}^3_2\text{He}$.

Step 2: Calculate the mass defect for part (b) Use the masses exactly as provided in the question. Add both reactant masses and both product masses before taking their difference:

$$\begin{aligned} m_{\text{initial}} &= 2(2.014102) = 4.028204 \text{ u}, \\ m_{\text{final}} &= 3.016049 + 1.008665 = 4.024714 \text{ u}, \\ \Delta m &= 4.028204 - 4.024714 = 0.003490 \text{ u}. \end{aligned}$$

The products have less total rest mass than the reactants. This decrease in rest mass supplies the released energy. If the supplied hydrogen and helium values are treated as atomic masses, their electron masses cancel because there are two electrons on each side.

Step 3: Convert the mass defect into released energy Multiplying the mass defect by the given mass-energy conversion factor gives

$$\begin{aligned} Q &= (0.003490 \text{ u})(931.5 \text{ MeV/u}) \\ &= 3.250935 \text{ MeV}. \end{aligned}$$

The unit u cancels, leaving energy in MeV . Since $Q > 0$, the reaction is exoergic: the released energy appears chiefly as kinetic energy of the outgoing helium nucleus and neutron.

Step 4: Conclusion (a) $A = 3$, so X is helium-3.

(b) Using the supplied masses, the energy released per reaction is $Q \simeq 3.25 \text{ MeV}$.

Quick Tip to Solve: Balance the upper and lower nuclear numbers separately, then subtract the total product mass from twice the deuterium mass before multiplying by 931.5.

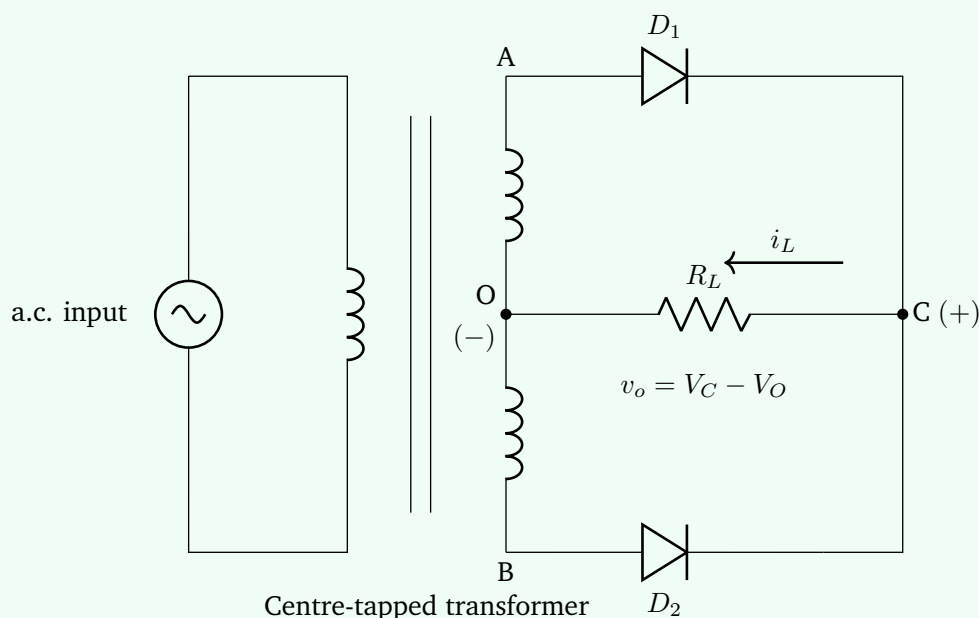
28. With the help of a circuit diagram, explain the working of a full wave rectifier. Depict the input and output waveforms. [3 marks]

Solution:

Concept:

- A p-n junction diode conducts when forward biased and blocks current when reverse biased. A full wave rectifier uses both half cycles of an alternating voltage to produce unidirectional load current.
- In a centre-tapped transformer, the secondary ends A and B have equal and opposite voltages relative to the centre tap O. For ideal diodes, the load voltage is $v_o = V_m |\sin \omega t|$, where V_m is the peak voltage of either half-secondary.

Step 1: Connect the two-diode rectifier Connect secondary ends A and B to the anodes of diodes D_1 and D_2 , respectively. Join their cathodes at C, and connect the load resistance R_L between C and centre tap O. The primary receives the alternating input; the transformer supplies the centre-tapped secondary. The output is measured across R_L , with C positive relative to O.

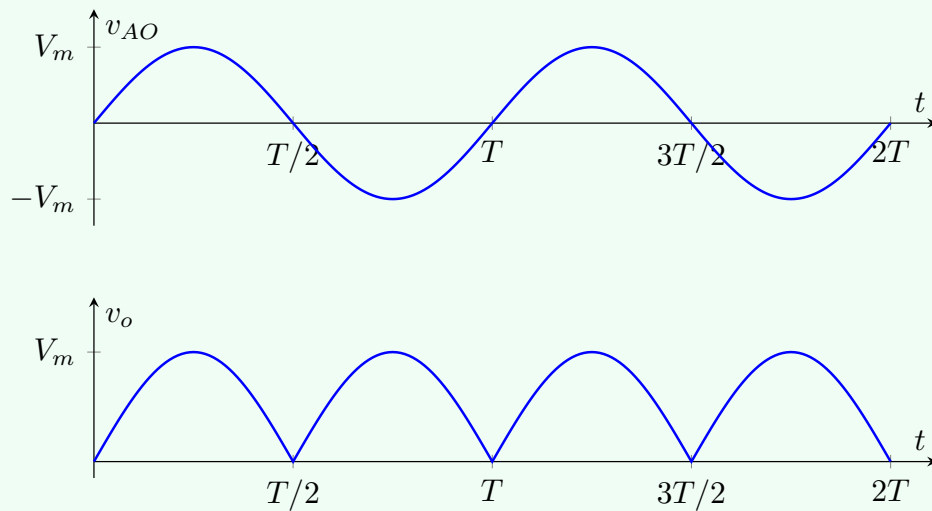


Centre-tapped full wave rectifier; both diode cathodes join at C.

Step 2: Follow the positive half cycle When A is positive and B is negative relative to O, D_1 is forward biased and D_2 is reverse biased. Conventional current flows through A, D_1 , C and R_L , returning to O through the upper half-secondary. Hence the load current flows from C to O and produces a positive output pulse.

Step 3: Follow the negative half cycle In the next half cycle, B becomes positive and A becomes negative relative to O. Now D_2 conducts and D_1 blocks. Current follows B, D_2 , C and R_L , returning to O through the lower half-secondary. The load current again flows from C to O: its direction does not reverse.

Step 4: Compare the input and output waveforms The first graph represents the sinusoidal secondary input $v_{AO} = V_m \sin \omega t$. The second shows the voltage across the load for ideal diodes. Both half cycles appear as positive pulses, so the output has two pulses per input cycle and ripple frequency $2f$, where f is the input frequency. It is pulsating d.c.; a filter would be required to make it smoother.



Sinusoidal input and full wave rectified output, with ideal diodes.

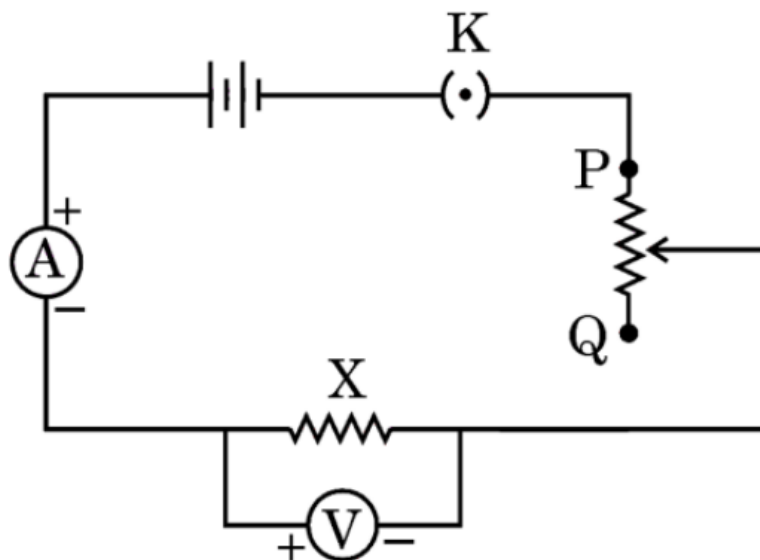
Step 5: Conclusion The diodes conduct alternately, giving current through R_L in the same direction during both half cycles. Thus a full wave rectifier converts a.c. into pulsating d.c. with output ripple frequency twice the input frequency.

Quick Tip to Solve: Trace each conducting path from the positive secondary end to the centre tap; both paths must cross the load in the same direction.

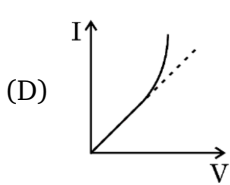
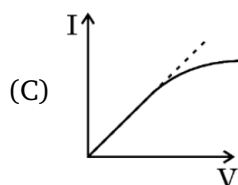
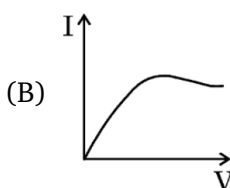
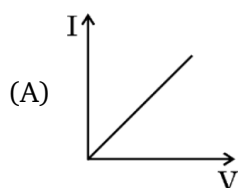
Section D (8 marks)

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

29. A student sets up the circuit as shown in the figure to find the value of unknown resistance X and records a set of readings of the voltmeter and the ammeter by using the rheostat. [4 marks]



29(i). If resistor X were made of manganin and readings for V and I are taken without switching off the circuit, the graph between V and I will be as: [1 mark]



Correct Answer: (A)

Solution:

Concept:

- Ohm's law gives $V = IX$, where X is the resistance. For fixed resistance, current is directly proportional to potential difference.
- Manganin has a very small temperature coefficient of resistance, so moderate heating during continuous readings causes negligible change in X .

Step 1: Relate the graph slope to resistance The printed graphs have current I vertically and voltage V horizontally. Thus $I = V/X$, and the slope of the graph is $1/X$. Because manganin's resistance remains approximately constant, this slope is constant and the line passes through the origin.

Step 2: Compare the four plotted shapes Option (A) is a straight line through the origin. Option (B) bends over and then falls, (C) bends below the straight-line continuation, and (D) bends above it. All three curved options require the effective resistance to vary appreciably with the reading, which is not the expected behaviour of manganin here.

Step 3: Conclusion The current-voltage graph is the straight line through the origin shown in (A). Hence, the correct option is (A).

Quick Tip to Solve: Check the axis order first: an I-versus-V graph has slope $1/X$, while a V-versus-I graph has slope X .

29(ii). Error in the value of X obtained from different sets of voltmeter and ammeter readings, is: [1 mark]

- (A) due to error in voltmeter reading only.
- (B) due to error in ammeter reading only.
- (C) equal to the sum of error in voltmeter reading and error in ammeter reading.
- (D) equal to error in voltmeter reading divided by the error in ammeter reading.

Correct Answer: (C) equal to the sum of error in voltmeter reading and error in ammeter reading.

Solution:

Concept:

- The measured resistance is $X = V/I$, where V and I are the voltmeter and ammeter readings.
- For a quotient, the maximum fractional error is the sum of the fractional errors of its measured quantities, to first order in small errors.

Step 1: Apply the error propagation rule Let ΔV and ΔI be the positive bounds on the measurement errors. Since either reading affects the ratio, the maximum fractional error obeys

$$\frac{\Delta X}{X} = \frac{\Delta V}{V} + \frac{\Delta I}{I}.$$

Multiplying by 100 gives the same addition rule for percentage errors.

Step 2: Interpret the options precisely The sum in option (C) is understood as the sum of fractional or percentage errors. It is not a sum of absolute voltmeter and ammeter errors, which have different units. Options (A) and (B) each omit one measurement's contribution; option (D) incorrectly divides the errors instead of adding their fractional values.

Step 3: Conclusion The maximum fractional error in X is the sum of the fractional errors in V and I . With this standard error-propagation interpretation, the correct option is (C).

Quick Tip to Solve: For $X = V/I$, add the percentage uncertainties; never add an uncertainty in volts directly to one in amperes.

29(iii). If the movable end of rheostat is moved towards P, then:

[1 mark]

- (A) reading in ammeter decreases and reading in voltmeter increases.
- (B) readings in both voltmeter and ammeter increase.
- (C) reading in ammeter increases and reading in voltmeter decreases.
- (D) readings in both voltmeter and ammeter decrease.

Correct Answer: (B) readings in both voltmeter and ammeter increase.

Solution:

Concept:

- The rheostat's effective resistance is proportional to the length of resistance wire between its connected fixed terminal and its slider.
- For a fixed battery voltage, reducing series resistance increases circuit current. The voltage across the unchanged resistor X is $V_X = IX$.

Step 1: Identify the active rheostat length In the printed circuit, P is the connected fixed end; Q is not connected to the circuit. Only the wire from P to the slider is in series with X . Moving the slider towards P shortens this wire and reduces the rheostat resistance.

Step 2: Predict both meter readings With a smaller total series resistance, current increases, so the ammeter reading rises. Since X remains fixed, $V_X = IX$ also increases and the voltmeter reading rises. Thus (A) and (C), which predict opposite changes, are inconsistent with Ohm's law for X ; (D) would require an increase in the effective rheostat resistance.

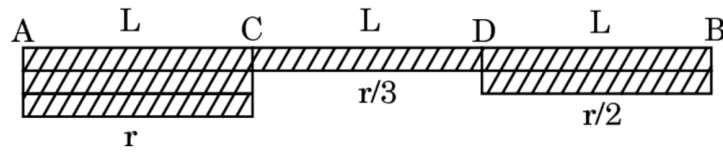
Step 3: Conclusion The readings of both the ammeter and the voltmeter increase. Hence, the correct option is (B).

Quick Tip to Solve: Trace the fixed terminal that is actually wired: here P-to-slider is active, so moving towards P reduces resistance.

29(iv)(a). Suppose the unknown resistance X is replaced by a wire made of the same metal. This wire consists of three parts, of the same length L but has radii r , $r/3$ and $r/2$ as shown in the figure.

For a particular setting of the rheostat, let v_1 , v_2 and v_3 be the value of drift velocities in parts AC, CD and DB. Then:

[1 mark]



(A) $v_1 > v_2 > v_3$

(B) $v_2 > v_3 > v_1$

(C) $v_3 > v_2 > v_1$

(D) $v_1 = v_2 = v_3$

Correct Answer: (B) $v_2 > v_3 > v_1$

Solution:

Concept:

- In steady state, the same current passes through all three sections connected in series; charge cannot continuously accumulate at a junction.
- The magnitude of drift velocity is $v_d = I/(neA)$, where n is the number density of conduction electrons, e the elementary charge and A the cross-sectional area.

Step 1: Compare the cross-sectional areas All sections are made of the same metal, so their electron number density n is the same. For radii r , $r/3$ and $r/2$,

$$A_1 : A_2 : A_3 = \pi r^2 : \frac{\pi r^2}{9} : \frac{\pi r^2}{4} = 1 : \frac{1}{9} : \frac{1}{4}.$$

Step 2: Use the common current Since both I and n are common, drift speed is inversely proportional to area. Therefore

$$v_1 : v_2 : v_3 = 1 : 9 : 4.$$

The narrowest part CD has the greatest drift speed and the widest part AC the least. Equal current does not imply equal drift speed, so (D) fails; (A) and (C) also contradict this inverse-area dependence.

Step 3: Conclusion The drift speeds satisfy $v_2 > v_3 > v_1$. Hence, the correct option is (B).

Quick Tip to Solve: In a single wire of one metal, square the radius ratios and invert them: radii 1:1/3:1/2 give drift speeds 1:9:4.

29(iv)(b). Consider the same wire, as shown in figure in question (iv) (a) connected in place of X. For a particular setting of rheostat, let E_1 , E_2 and E_3 be the value of electric fields in part AC, CD and DB. Then: [1 mark]

- (A) $E_1 = E_2 = E_3$
 (B) $E_3 > E_2 > E_1$
 (C) $E_2 > E_3 > E_1$
 (D) $E_1 > E_2 > E_3$

Correct Answer: (C) $E_2 > E_3 > E_1$

Solution:

Concept:

- The microscopic form of Ohm's law is $E = \rho J$, where E is electric-field magnitude, ρ the resistivity and J the current density.
- For a wire carrying steady current I , $J = I/A$. Sections of the same metal have the same resistivity under the stated common conditions.

Step 1: Express field in terms of area The three sections are in series, so the same current I crosses each. Consequently,

$$E_i = \frac{\rho I}{A_i}.$$

The common factors ρ and I cancel when fields are compared; the smaller the cross-sectional area, the greater the field required to maintain that current.

Step 2: Insert the three radii For AC, CD and DB the radii are r , $r/3$ and $r/2$, respectively. Hence

$$E_1 : E_2 : E_3 = \frac{1}{\pi r^2} : \frac{9}{\pi r^2} : \frac{4}{\pi r^2} = 1 : 9 : 4.$$

Equal lengths do not make the fields equal, so (A) fails. Options (B) and (D) place the largest field in a section other than the narrowest section CD and therefore also fail.

Step 3: Conclusion The electric-field magnitudes satisfy $E_2 > E_3 > E_1$. Hence, the correct option is (C).

Quick Tip to Solve: For series sections of the same metal, both drift speed and electric field vary as the inverse square of the radius.

30. An astronomical telescope consists of two converging lenses. One of them of large aperture and large focal length is called objective lens and the other one, of smaller focal length and smaller aperture is called the eyepiece. It is used to see distant objects which are not seen clearly with naked eyes. The image formed by the objective lens acts as an object for the eyepiece and the final image produced by the eyepiece is magnified. [4 marks]

30(i). The images formed by the objective lens and the eyepiece are respectively: [1 mark]

- (A) virtual, real
- (B) real, virtual
- (C) virtual, virtual
- (D) real, real

Correct Answer: (B) real, virtual

Solution:

Concept:

- A converging objective collects nearly parallel rays from a distant object and brings them to a real image near its focal plane.
- The eyepiece acts as a magnifier: the intermediate image is at or within its focal distance, so the observer sees a virtual final image.

Step 1: Identify the objective image Rays from a distant object actually converge after passing through the objective. Their meeting points form a real, inverted intermediate image. Thus options (A) and (C), which call this image virtual, are eliminated.

Step 2: Identify the eyepiece image The eyepiece views this intermediate image as its object. In normal adjustment it sends out parallel rays and gives the virtual final image at infinity; for a final image at the near point, it gives a finite virtual image. Therefore the final image is not real, which excludes option (D).

Step 3: Conclusion The objective forms a real image and the eyepiece forms a virtual image. Hence, the correct option is (B).

Quick Tip to Solve: Follow the two lenses in order: the objective forms the real intermediate image; the eyepiece magnifies it for the eye.

30(ii). The magnification produced by the telescope does not depend upon the: [1 mark]

- (A) colour of light
- (B) focal length of objective lens
- (C) focal length of eyepiece
- (D) apertures of objective lens and eyepiece

Correct Answer: (D) apertures of objective lens and eyepiece

Solution:

Concept:

- In normal adjustment, the magnitude of the angular magnifying power is $M = f_o/f_e$, where f_o and f_e are the objective and eyepiece focal lengths.
- Lens aperture controls the admitted light and contributes to resolving ability; it does not occur in

the telescope's angular magnification formula.

Step 1: Identify the quantities in the magnification formula Increasing f_o increases the angular magnification, while increasing f_e decreases it. Hence the focal lengths in options (B) and (C) do affect magnification. The focal lengths of refracting lenses can depend on the colour of light because the refractive index is wavelength dependent; colour is therefore not the generally independent factor sought here.

Step 2: Separate magnification from aperture effects Neither the objective diameter nor the eyepiece diameter appears in $M = f_o/f_e$. Changing these apertures, while retaining the focal lengths, affects light collection or the usable field rather than the geometrical angular magnification. A larger objective can make a faint object brighter and improve resolution without increasing its angular magnification.

Step 3: Conclusion The magnification does not depend on the apertures of the objective and eyepiece. Hence, the correct option is (D).

Quick Tip to Solve: Use the focal-length ratio for magnification; use the objective aperture when considering light collection or resolution.

30(iii). Which of the following statements is not correct for this telescope?

[1 mark]

- (A) The focal length of objective lens (f_o) is larger than the focal length of eyepiece (f_e).
- (B) Its magnifying power can be increased by increasing the focal length of objective lens (f_o).
- (C) The distance between two lenses is more than $(f_o + f_e)$.
- (D) The magnifying power can be decreased by increasing the focal length of eyepiece.

Correct Answer: (C) The distance between two lenses is more than $(f_o + f_e)$.

Solution:

Concept:

- For an astronomical telescope in normal adjustment, $M = f_o/f_e$ is the magnitude of magnifying power and $L = f_o + f_e$ is the lens separation.
- For a virtual final image at the least distance of distinct vision D , the intermediate image is within the eyepiece focus, giving $L = f_o + f_e D/(D + f_e) < f_o + f_e$.

Step 1: Test the focal-length statements The telescope uses a long-focal-length objective and a short-focal-length eyepiece, so $f_o > f_e$: statement (A) is correct. From $M = f_o/f_e$, increasing f_o increases magnifying power, whereas increasing f_e decreases it. Statements (B) and (D) are therefore also correct.

Step 2: Test the separation statement The objective forms the intermediate image at its rear focus. In normal adjustment this point is also the front focus of the eyepiece, so the separation equals $f_o + f_e$. For near-point viewing the eyepiece is moved closer to the objective, making the separation smaller. In neither standard viewing arrangement is the separation greater than $f_o + f_e$, as claimed in (C).

Step 3: Conclusion Statement (C) is not correct: the lens separation is equal to $f_o + f_e$ in normal adjustment and smaller for near-point viewing. Hence, the correct option is (C).

Quick Tip to Solve: For two converging lenses in normal adjustment, add the focal lengths for tube length and divide them for magnifying power.

30(iv)(a). An astronomical telescope has objective lens and eyepiece of focal lengths 80 cm and 4 cm respectively. To view the image in normal adjustment, the lenses must be separated by a distance of: [1 mark]

- (A) 84 cm
- (B) 76 cm
- (C) 20 cm
- (D) 320 cm

Correct Answer: (A) 84 cm

Solution:

Concept:

- Normal adjustment means that the final image is at infinity, allowing the eye to view it without accommodation.
- The objective's rear focal plane coincides with the eyepiece's front focal plane; for two converging lenses their separation is $L = f_o + f_e$.

Step 1: Set the normal-adjustment condition Parallel rays from the distant object form a real intermediate image $f_o = 80$ cm behind the objective. The eyepiece must be another $f_e = 4$ cm beyond this image so that the emerging rays are parallel. The two positive distances are added.

Step 2: Substitute the focal lengths The required lens separation is

$$L = f_o + f_e = 80 \text{ cm} + 4 \text{ cm} = 84 \text{ cm}.$$

The difference 76 cm does not apply to this telescope with a converging eyepiece. The ratio $80/4 = 20$ is its dimensionless magnifying power, not a length; the product of focal lengths cannot give the required separation either.

Step 3: Conclusion The lenses must be separated by 84 cm. Hence, the correct option is (A).

Quick Tip to Solve: When the final image is at infinity and both telescope lenses converge, add their focal lengths to get the separation.

OR

30(iv)(b). Consider the telescope described in question (iv) (a). Its magnifying power in normal adjustment will be: [1 mark]

- (A) 320
- (B) 84
- (C) 76
- (D) 20

Correct Answer: (D) 20

Solution:

Concept:

- The angular magnifying power in normal adjustment has magnitude $M = f_o/f_e$, where f_o and f_e are the objective and eyepiece focal lengths.

- Magnifying power is an angle ratio and is dimensionless. The signed angular magnification is negative because the astronomical telescope produces an inverted image.

Step 1: Select the normal-adjustment formula The final image lies at infinity in normal adjustment, so use the ratio of focal lengths without a near-point correction factor. From part (iv)(a), the objective focal length is 80 cm and the eyepiece focal length is 4 cm.

Step 2: Calculate the magnifying power The focal lengths are already in the same unit, which cancels in the ratio:

$$M = \frac{f_o}{f_e} = \frac{80 \text{ cm}}{4 \text{ cm}} = 20.$$

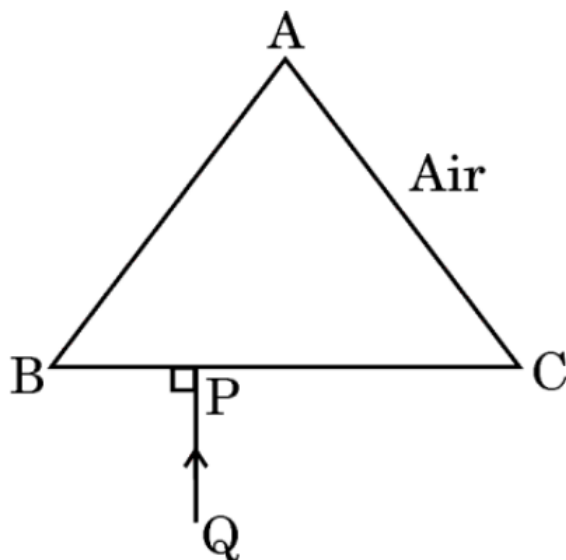
The signed value would be -20 , indicating inversion; the positive options refer to the magnitude. The product 320, sum 84, and difference 76 of the numerical focal lengths do not represent the angular magnifying power.

Step 3: Conclusion The magnifying power in normal adjustment is 20. Hence, the correct option is (D).

Quick Tip to Solve: Divide the longer objective focal length by the shorter eyepiece focal length, using identical units, to obtain telescope magnifying power.

Section E (15 marks)

- 31(a).** (i) Define refractive index of a medium in terms of speed of light.
- (ii) Derive the relation for the refractive index (μ) of a prism in terms of angle of minimum deviation (δ_m) and angle of prism (A).
- (iii) A ray of light QP is incident normally on the face BC of a triangular prism ABC of refractive index 1.5 kept in air, as shown in the figure. Trace the path of the ray as it passes through the prism and give relevant explanation. [5 marks]



Solution:

Concept:

- The absolute refractive index is $\mu = c/v$, where c is the speed of light in vacuum and v is its speed in the medium.
- For a prism in air, Snell's law gives $\sin i = \mu \sin r_1$ and $\mu \sin r_2 = \sin e$. Here i, e are the external incidence and emergence angles, while r_1, r_2 are the internal refraction angles, all measured from the respective normals.
- Prism geometry gives $r_1 + r_2 = A$ and total deviation $\delta = i + e - A$. At minimum deviation the ray path is symmetric.
- At a prism-air boundary, the critical angle θ_c obeys $\sin \theta_c = 1/\mu$. Total internal reflection requires incidence from the denser medium at an angle greater than θ_c .

Step 1: (i) Define the refractive index The absolute refractive index of a medium is the ratio of the speed of light in vacuum to the speed of light in that medium:

$$\mu = \frac{c}{v}.$$

It is dimensionless because it is a ratio of two speeds. A larger refractive index corresponds to a smaller speed of light in the medium. For refraction relative to another medium, the corresponding

relative index is the ratio of the two speeds.

Step 2: (ii) Relate the prism angles and the deviation Draw normals to the two refracting faces at the entry and exit points. The angle between the appropriate normals is supplementary to the prism angle A . The quadrilateral formed by the two faces, these normals and the internal ray then gives

$$r_1 + r_2 = A.$$

At the first face the ray turns through $i - r_1$, and at the second face it turns through $e - r_2$, in the same overall sense. Hence

$$\begin{aligned}\delta &= (i - r_1) + (e - r_2) \\ &= i + e - (r_1 + r_2) \\ &= i + e - A.\end{aligned}$$

The printed expression “minimum derivation” refers to the minimum deviation δ_m .

Step 3: (ii) Apply the minimum-deviation condition As the prism is rotated, the deviation first decreases and then increases. At its minimum, the path through the prism is symmetric under reversal: $i = e$ and $r_1 = r_2$. Thus

$$r_1 = r_2 = \frac{A}{2}, \quad \delta_m = 2i - A, \quad i = \frac{A + \delta_m}{2}.$$

Apply Snell’s law at the first face, taking the refractive index of air as unity, and substitute these angles:

$$\mu = \frac{\sin i}{\sin r_1} = \frac{\sin\left(\frac{A + \delta_m}{2}\right)}{\sin\left(\frac{A}{2}\right)}.$$

This expression gives the refractive index of the prism relative to air, for the wavelength used.

Step 4: (iii) Identify the geometric assumption and entry path The printed figure contains no numerical prism angles or equal-side labels. Consequently, a unique numerical ray trace cannot be inferred from the refractive index alone. The usual intended construction takes ABC to be an equilateral prism; the following trace and diagram explicitly use that assumption, so each prism angle is 60° .

The incident ray QP is normal to BC , so its incidence angle there is zero. Snell’s law gives zero refraction angle; it continues vertically along PR to face AB . Its speed changes on entering the prism, but its direction does not.

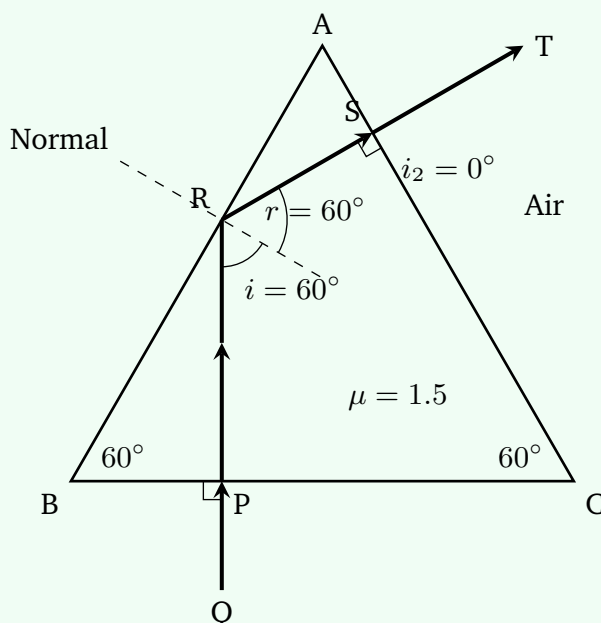
Step 5: (iii) Compare the incidence at AB with the critical angle For the equilateral construction, the angle between the upward ray and the normal to AB is 60° . The critical angle at the prism–air boundary is

$$\theta_c = \sin^{-1}\left(\frac{1}{1.5}\right) = \sin^{-1}\left(\frac{2}{3}\right) \simeq 41.8^\circ.$$

Since $60^\circ > 41.8^\circ$, the ray undergoes total internal reflection at R . The reflected ray RS makes 60° with the normal to AB , by the law of reflection, and travels towards face AC .

Step 6: (iii) Trace emergence through AC In the equilateral geometry, RS makes 30° with the base BC and is perpendicular to face AC . Its angle of incidence at S is therefore zero. It emerges along ST without angular deviation at that face, following the path $Q \rightarrow P \rightarrow R \rightarrow S \rightarrow T$.

For a general triangular prism, however, the incidence at AB is $\angle ABC$, so total internal reflection there requires $\angle ABC > 41.8^\circ$. The direction and possible further reflection at AC depend on the remaining prism angle. Thus the 60° incidence and normal emergence shown below are conditional on the equilateral assumption, not additional data printed in the question.



Ray trace assuming an equilateral prism: total internal reflection at R and normal emergence at S . The printed figure does not specify its angles.

Step 7: Conclusion $\mu = \frac{c}{v}$, and at minimum deviation

$$\mu = \frac{\sin((A + \delta_m)/2)}{\sin(A/2)}.$$

For the intended equilateral-prism construction, QP enters BC normally, suffers total internal reflection at AB because $60^\circ > 41.8^\circ$, and emerges normally from AC . The printed unlabelled triangle alone does not establish the equilateral geometry.

Quick Tip to Solve: Draw the normal at each struck face before deciding between refraction and total internal reflection. Normal entry does not imply normal incidence at the next face; that angle depends on the prism geometry.

31(b). (i) What is the difference between a ray and a wavefront?

(ii) A plane wave is incident on a reflecting surface. Using Huygens principle, show how it is reflected from the surface. Hence, verify the law of reflection.

(iii) Depict refraction of a plane wave by a convex lens.

[5 marks]

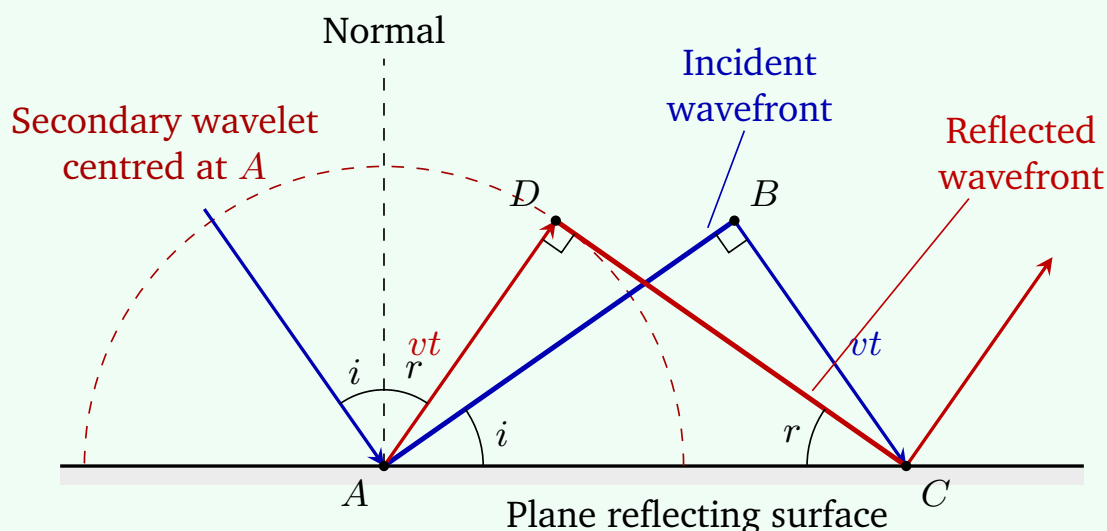
Solution:

Concept:

- A wavefront is the locus of points of a wave that have the same phase at a given instant. A ray indicates the direction of propagation of light and is normal to the wavefront in an isotropic medium.
- Huygens' principle: every point on a wavefront acts as a source of secondary wavelets. The forward envelope of these wavelets gives the new wavefront after a time interval t .
- In the same medium, incident and reflected light have the same speed v . A wavelet therefore has radius vt after time t .
- A convex lens transforms a plane wavefront incident parallel to its principal axis into a converging spherical wavefront, whose centre is at the principal focus on the other side of the lens, in the paraxial approximation.

Step 1: (i) Distinguish a ray from a wavefront A ray is a directed line representing the path and direction in which light energy travels. A wavefront is a surface joining all points which oscillate in the same phase at one instant. Thus, a ray describes a propagation direction, while a wavefront describes a surface of constant phase. In an isotropic medium, rays are perpendicular to the wavefront. A plane wavefront has parallel rays normal to its plane; a spherical wavefront has radial rays normal to its surface. The lines used to draw wavefronts in a two-dimensional figure are sections of these surfaces.

Step 2: (ii) Construct the reflected wavefront Let AB be a plane incident wavefront and AC the plane reflecting surface. Point A reaches the surface first. During the next time interval t , point B travels along the incident ray to C , so $BC = vt$. Meanwhile, the secondary wavelet emitted from A spreads back into the incident medium with radius $AD = vt$. Draw the tangent CD from C to this wavelet. The radius AD is perpendicular to the tangent CD . The common tangent envelope of the reflected secondary wavelets is the new plane reflected wavefront CD . Its normal AD gives the direction of the reflected light. All points of the reflecting surface between A and C also produce wavelets, with smaller radii because they are reached later.



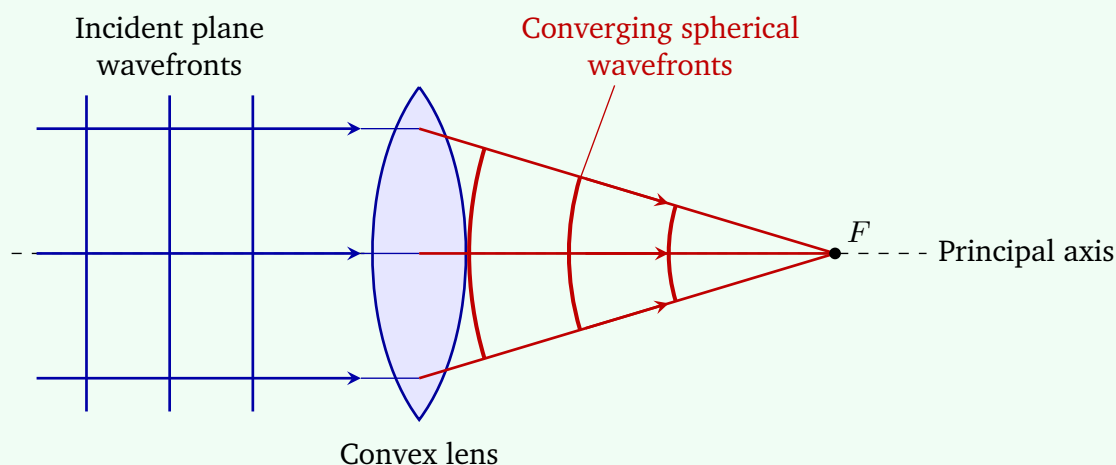
Huygens' construction: AB is incident, CD is reflected, and $BC = AD = vt$.

Step 3: (ii) Deduce the law of reflection The incident ray BC is perpendicular to AB , so $\triangle ABC$ is right-angled at B . Similarly, $AD \perp CD$, so $\triangle ADC$ is right-angled at D . They have the common hypotenuse AC and equal sides $BC = AD = vt$. The angle between the incident wavefront AB and the reflecting surface is the angle of incidence i , because their respective normals are the incident ray and the surface normal. Likewise, the angle between CD and the surface is the angle of reflection r . Hence,

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

Since i and r lie between 0° and 90° , this equality gives $i = r$. The incident ray, reflected ray and normal to the surface lie in the plane of this construction. Thus both statements of the law of reflection are verified.

Step 4: (iii) Depict refraction through a convex lens Take plane wavefronts whose direction of propagation is parallel to the principal axis of a convex lens. The central portion travels through a greater thickness of glass than the portions near the edges. Since light travels more slowly in glass than in air, the centre is delayed more than the edges. Consequently, the emerging wavefront bends into a converging spherical shape, as shown in section below. The refracted rays, being perpendicular to these wavefronts, converge at the principal focus F . Successive wavefronts before the focus have decreasing radii, with their common centre at F . This standard construction assumes a thin lens and paraxial rays; after passing through the focus, the wavefronts become divergent.



Plane wavefronts become converging spherical wavefronts after a convex lens.

Step 5: Conclusion A ray gives the direction of propagation; a wavefront is a surface of equal phase. Huygens' construction gives $BC = AD = vt$ and hence $i = r$, with the incident ray, reflected ray and normal coplanar. A convex lens changes an incident plane wavefront into a converging spherical wavefront centred at its principal focus.

Quick Tip to Solve: For reflection, use the same elapsed time for BC and the wavelet radius AD , then compare the two right triangles. For the lens, draw wavefronts perpendicular to rays and curve them as arcs centred at F .

32(a). (i) Define the terms (I) resonant frequency, and (II) power factor of a series LCR circuit. For what value of the power factor will the power dissipated in the circuit be maximum?

(ii) An inductor of $\frac{5}{\pi}$ H, a capacitor of $\frac{50}{\pi} \mu\text{F}$ and a resistor of 400Ω are connected in series across an ac voltage $v = 140 \sin(100\pi t)$ V. Calculate:

(I) impedance of the circuit, and

(II) rms value of current that flows in the circuit.

(Take $\sqrt{2} = 1.4$)

[5 marks]

Solution:

Concept:

- For a series LCR circuit, the inductive and capacitive reactances are $X_L = \omega L$ and $X_C = 1/(\omega C)$, where $\omega = 2\pi f$ is the angular frequency of the supply.
- The impedance magnitude is $Z = \sqrt{R^2 + (X_L - X_C)^2}$. The rms current is $I_{\text{rms}} = V_{\text{rms}}/Z$, with $V_{\text{rms}} = V_0/\sqrt{2}$ for a sinusoidal voltage of peak value V_0 .
- The power factor is $\cos \phi = R/Z$, where ϕ is the phase difference between applied voltage and current. Average power is $P = V_{\text{rms}} I_{\text{rms}} \cos \phi$.

Step 1: (i)(I) Define the resonant frequency The resonant frequency is the frequency of the applied alternating voltage at which the inductive and capacitive reactances of a series LCR circuit become equal. Their opposite reactive voltage drops cancel, so the impedance is purely resistive and has its minimum value R . Hence, for a fixed voltage amplitude, the current amplitude is maximum at

resonance. Setting the reactances equal gives

$$\omega_0 L = \frac{1}{\omega_0 C} \Rightarrow \omega_0 = \frac{1}{\sqrt{LC}}, \quad f_0 = \frac{1}{2\pi\sqrt{LC}}.$$

Step 2: (i)(II) Define the power factor and find its maximum-power value The power factor is the cosine of the phase difference between the applied alternating voltage and the current. Equivalently, it is the ratio of the average power consumed to the product of the rms voltage and rms current:

$$\cos \phi = \frac{R}{Z} = \frac{P}{V_{\text{rms}} I_{\text{rms}}}.$$

For a given supply rms voltage and resistance, the dissipated power is

$$P = I_{\text{rms}}^2 R = \frac{V_{\text{rms}}^2 R}{R^2 + (X_L - X_C)^2}.$$

This is greatest when $X_L = X_C$, making the denominator smallest. Voltage and current are then in phase, $\phi = 0$, and the power factor is unity. Ideal inductors and capacitors exchange energy with the supply; only the resistor dissipates average power.

Step 3: (ii)(I) Read the angular frequency and calculate the reactances Compare $v = 140 \sin(100\pi t)$ V with $v = V_0 \sin(\omega t)$. Thus, $V_0 = 140$ V and $\omega = 100\pi$ rad s⁻¹. Use the printed values $L = (5/\pi)$ H and $C = (50/\pi) \times 10^{-6}$ F:

$$X_L = \omega L = (100\pi) \frac{5}{\pi} = 500 \Omega,$$

$$X_C = \frac{1}{\omega C} = \frac{1}{(100\pi)(50/\pi) \times 10^{-6}} = 200 \Omega.$$

The net reactance is inductive because $X_L > X_C$; its magnitude is $500 - 200 = 300 \Omega$. The reactances subtract because their voltage contributions have opposite phases.

Step 4: Combine resistance and net reactance Resistance and net reactance are perpendicular components of impedance, so they must be combined by a square root of the sum of squares:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$= \sqrt{400^2 + 300^2} = \sqrt{250000} \Omega = 500 \Omega.$$

The numerical circuit is not at resonance, since its two reactances are unequal. Its power factor is $R/Z = 400/500 = 0.8$, consistent with a nonzero phase difference.

Step 5: (ii)(II) Convert the peak voltage and calculate the rms current The coefficient of the sine is the peak voltage, so first convert it to rms voltage using the approximation given in the question:

$$V_{\text{rms}} = \frac{140}{\sqrt{2}} = \frac{140}{1.4} = 100 \text{ V}.$$

Apply the rms form of Ohm's law for the ac circuit:

$$I_{\text{rms}} = \frac{V_{\text{rms}}}{Z} = \frac{100}{500} = 0.20 \text{ A}.$$

As a check, the peak current is $140/500 = 0.28$ A, whose rms value is $0.28/1.4 = 0.20$ A.

Step 6: Conclusion (i) Resonance occurs at $f_0 = 1/(2\pi\sqrt{LC})$, when $X_L = X_C$. The power factor is $\cos \phi = R/Z$, and maximum power dissipation occurs at power factor 1. (ii) For the given circuit,

$$Z = 500\ \Omega \text{ and } I_{\text{rms}} = 0.20\ \text{A}.$$

Quick Tip to Solve: Retain the printed π denominators in both L and C ; they cancel the π in ω . The resulting 300, 400, 500 impedance triangle gives Z immediately. Convert the peak voltage to rms before using $I_{\text{rms}} = V_{\text{rms}}/Z$.

OR

32(b). (i) Draw a labelled diagram of a step-up transformer. Obtain the ratio of secondary voltage to primary voltage in terms of number of turns in the two coils.

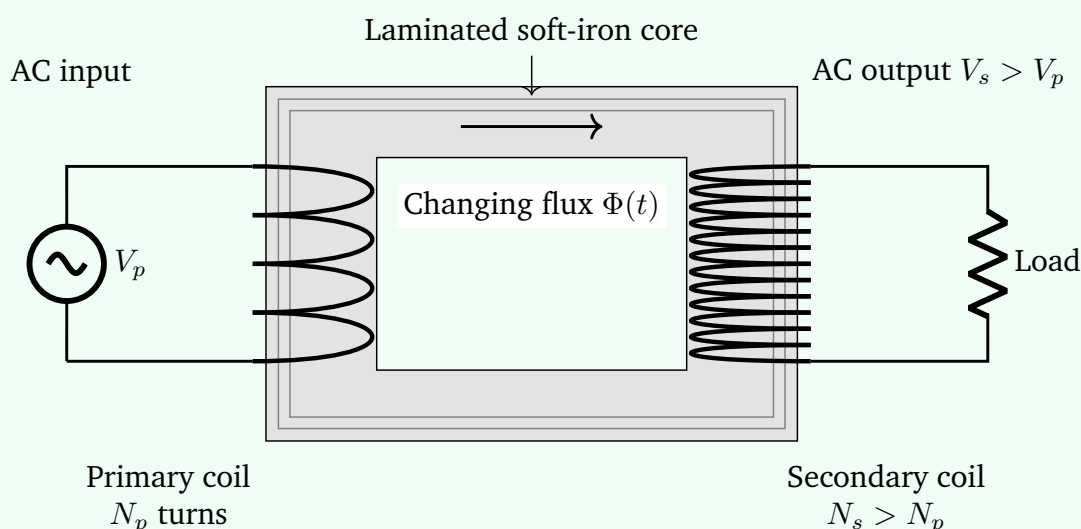
(ii) The number of turns in the primary and the secondary coil of an ideal transformer are 100 and 5000 respectively. If 3.3 kW power is supplied to the transformer at 220 V, find (I) current in the primary coil, and (II) output voltage. [5 marks]

Solution:

Concept:

- A transformer works on mutual induction: alternating current in the primary produces a changing magnetic flux through a common laminated soft-iron core, inducing an emf in the secondary.
- If each turn of both coils links the same flux $\Phi(t)$, Faraday's law gives $e_p = -N_p d\Phi/dt$ and $e_s = -N_s d\Phi/dt$, where N_p and N_s are the primary and secondary turns.
- For an ideal transformer, the ratio of rms terminal voltages is $V_s/V_p = N_s/N_p$. The standard ideal-transformer power relation used here is $P_{\text{in}} = V_p I_p = P_{\text{out}}$.

Step 1: (i) Draw and explain the step-up transformer The labelled diagram shows two insulated windings on a common laminated soft-iron core. The primary is connected to an alternating-voltage source; the secondary supplies a load. A step-up transformer has $N_s > N_p$, represented by more turns on the secondary side. Alternating primary current establishes a changing core flux that links both windings. The core provides a low-reluctance magnetic path, while its laminations reduce eddy-current losses. The coils are electrically separate; energy is transferred through the changing magnetic field.



Step-up transformer: the secondary has more turns than the primary; both share the changing core flux.

Step 2: (i) Derive the voltage ratio Let $\Phi(t)$ be the magnetic flux through each turn. Neglect flux

leakage, winding resistance and core losses. Applying Faraday's law to the two windings gives

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

Both expressions contain the same flux-change rate. Therefore, the induced-emf magnitudes, amplitudes and rms values have the same turns ratio:

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

In an ideal transformer the terminal-voltage magnitudes equal the corresponding induced-emf magnitudes, so

$$\boxed{\frac{V_s}{V_p} = \frac{N_s}{N_p}}.$$

Thus $N_s > N_p$ gives $V_s > V_p$, as required for a step-up transformer. This voltage increase does not create energy: the available secondary current decreases correspondingly for a fixed transmitted power.

Step 3: (ii)(I) Calculate the primary current The supplied power is $P_{\text{in}} = 3.3 \text{ kW} = 3300 \text{ W}$, and the primary voltage is $V_p = 220 \text{ V}$. Using the ideal-transformer power relation for the stated numerical data,

$$I_p = \frac{P_{\text{in}}}{V_p} = \frac{3300}{220} = 15 \text{ A}.$$

The quoted ac supply voltage and the calculated primary current are rms values.

Step 4: (ii)(II) Calculate the secondary voltage The primary has $N_p = 100$ turns and the secondary has $N_s = 5000$ turns. Hence the voltage multiplication factor is

$$\frac{N_s}{N_p} = \frac{5000}{100} = 50.$$

Substituting into the derived relation gives

$$V_s = V_p \frac{N_s}{N_p} = 220 \times 50 = 11000 \text{ V}.$$

As a consistency check, the ideal secondary current would be $I_s = 3300/11000 = 0.30 \text{ A}$; the output power remains $11000 \times 0.30 = 3300 \text{ W}$.

Step 5: Conclusion A step-up transformer has $N_s > N_p$, with $\boxed{V_s/V_p = N_s/N_p}$. For the given transformer, the primary current is $\boxed{I_p = 15 \text{ A}}$, and the output voltage is $\boxed{V_s = 11000 \text{ V} = 11 \text{ kV}}$.

Quick Tip to Solve: First calculate the turns ratio $5000/100 = 50$: multiply the input voltage by 50. Obtain the primary current from the input power and input voltage, converting kW to W first.

33(a). (i) Explain the following statements giving reason:

(I) An equipotential surface through a point is normal to the electric field at that point.

(II) When a dielectric is placed in an external electric field, the electric field inside the dielectric is less than that outside it.

(III) The potential difference between the plates of a charged parallel plate capacitor decreases when its plates are brought closer.

(ii) Obtain an expression for the work done to dissociate the system of three charges q , $-4q$ and $2q$ placed at the vertices A, B and C respectively of an equilateral triangle of side 'a'. [5 marks]

Solution:

Concept:

- Electric potential and field are related by $dV = -\vec{E} \cdot d\vec{l}$. An equipotential surface has the same potential at all its points.
- A dielectric becomes polarised in an applied field. Its bound charges produce an induced field opposing the applied field inside the material.
- For a parallel plate capacitor, $C = \epsilon A/d$ and $V = Q/C$, where A is plate area, d is separation and ϵ is the intervening medium's permittivity.
- The electrostatic potential energy is the sum over distinct charge pairs: $U = \sum_{i < j} k q_i q_j / r_{ij}$, with $k = 1/(4\pi\epsilon_0)$. Slow external work with no change of kinetic energy is $W_{\text{ext}} = U_f - U_i$.

Step 1: (i)(I) Use displacement along an equipotential surface Consider an infinitesimal displacement $d\vec{l}$ tangent to the equipotential surface through the given point. Because the potential is constant along the surface, $dV = 0$. Thus

$$\vec{E} \cdot d\vec{l} = E dl \cos \theta = 0.$$

At a point where the electric field is nonzero, this requires $\theta = 90^\circ$ for every tangential direction. Therefore the field has no tangential component and is normal to the equipotential surface. Equivalently, a charge can be moved along that surface without electrostatic work.

Step 2: (i)(II) Account for dielectric polarisation The external field slightly separates the centres of positive and negative bound charges in nonpolar molecules, and tends to align existing dipoles in polar molecules. This polarisation gives rise to bound surface charges whose field inside the dielectric opposes the external field. If their field has magnitude E_p , then

$$E_{\text{inside}} = E_0 - E_p < E_0.$$

Here E_0 is the applied field without the dielectric. In the usual uniform-field arrangement with a linear dielectric of relative permittivity $K > 1$, $E_{\text{inside}} = E_0/K$. The reduction is due to partial cancellation by the induced field, not to the disappearance of the external field.

Step 3: (i)(III) Keep the capacitor charge fixed For a charged capacitor isolated from a battery, the charge Q remains fixed as the plates are moved. Neglecting edge effects and keeping the area and medium unchanged,

$$V = \frac{Q}{C} = \frac{Qd}{\epsilon A}.$$

Bringing the plates closer reduces d , increases the capacitance and therefore decreases V in direct proportion to d . The statement assumes an isolated capacitor: if an ideal battery remained connected, it would hold V constant while the charge changed.

Step 4: (ii) Add the three pair interaction energies The charges are $q_A = q$, $q_B = -4q$ and $q_C = 2q$;

all three separations equal a . Counting each pair once gives

$$\begin{aligned}U_i &= \frac{k}{a}(q_Aq_B + q_Bq_C + q_Cq_A) \\&= \frac{kq^2}{a}(-4 - 8 + 2) \\&= -\frac{10kq^2}{a}.\end{aligned}$$

The two unlike-charge pairs contribute negative energy, while the like-charge pair contributes positive energy. No additional factor of one-half is needed because no pair has been counted twice.

Step 5: (ii) Compare the separated and initial states To dissociate the system completely, separate all charges so that every pair distance tends to infinity. Using the standard zero of potential energy at infinite separation, $U_f = 0$. With the charges initially and finally at rest, the work supplied externally is

$$W_{\text{ext}} = U_f - U_i = 0 - \left(-\frac{10kq^2}{a}\right).$$

The required work is positive because energy must be supplied to raise the negative initial potential energy to zero. The electric field itself does an equal amount of negative work during this separation.

Step 6: Conclusion An equipotential surface is perpendicular to the local nonzero electric field; dielectric polarisation reduces the internal field; and reducing plate separation lowers the voltage of an isolated charged capacitor. The work required to dissociate the three-charge system is

$$W_{\text{ext}} = \frac{10q^2}{4\pi\epsilon_0 a}.$$

Quick Tip to Solve: For three charges, list AB, BC and CA once each with their signs. Dissociation work is the negative of their total initial potential energy; for a capacitor, identify whether charge or voltage is held fixed first.

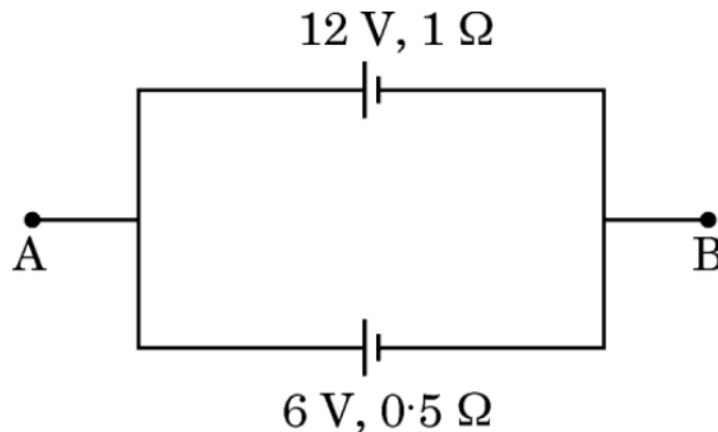
33(b). (i) Answer the following giving reason:

(I) The electron drift speed is estimated to be only a few mm/s for currents in the range of a few amperes. How, then, is the current established almost the instant a circuit is closed?

(II) A low voltage supply from which one needs high currents must have very low internal resistance. Why?

(III) The assertion that $V = IR$ is a statement of Ohm's law is not true. Why?

(ii) Two cells of emfs 12 V and 6 V are connected in parallel as shown in the figure. Their internal resistances are $1\ \Omega$ and $0.5\ \Omega$ respectively. Calculate the emf and internal resistance of the equivalent cell between points A and B. [5 marks]



Solution:

Concept:

- Drift speed describes the slow directed motion of charge carriers. The electric field that initiates this drift is established by a rapidly propagating electromagnetic disturbance.
- A cell of emf $\mathcal{E}$ and internal resistance r delivers terminal voltage $V = \mathcal{E} - Ir$ when supplying current I ; its internal heating rate is I^2r .
- Ohm's law requires $V \propto I$, and thus a constant $R = V/I$, for a conductor at fixed temperature and other physical conditions.
- The equivalent emf of a source network is its open-circuit terminal voltage. Its equivalent internal resistance is the resistance seen between the terminals when ideal voltage sources are replaced by short circuits.

Step 1: (i)(I) Distinguish drift from signal propagation A metallic wire already contains free electrons throughout its length, even before the switch is closed. Closing the circuit establishes an electric field around the circuit through an electromagnetic disturbance that propagates at a speed comparable to the speed of light in the surrounding medium. Electrons at different points therefore begin their local directed motion after a very small signal-transit time. The current does not have to wait for one electron to travel from the battery all the way to the appliance. Thus a drift speed of only a few mm s^{-1} is compatible with current starting almost immediately in an ordinary circuit. The establishment is very rapid, although it is not literally instantaneous.

Step 2: (i)(II) Limit the voltage lost inside the supply When a source supplies a large current I , the potential drop across its internal resistance is Ir , leaving the load with

$$V = \mathcal{E} - Ir.$$

Since the available emf is already small, even a modest internal resistance can consume a large fraction of it. To maintain a useful terminal voltage at high current, the source must satisfy $Ir \ll \mathcal{E}$, so r must be very small. This also limits the internal heating loss I^2r . Equivalently, for a load of resistance R_L , $I = \mathcal{E}/(R_L + r)$, so a large r restricts the obtainable current.

Step 3: (i)(III) State the condition missing from the bare equation The equation $V = IR$ by itself may simply define the ratio $R = V/I$ at an operating point. That ratio can vary with voltage, current or temperature, so the equation alone does not establish Ohm's law. Ohm's law asserts that, with temperature and other physical conditions fixed, the current through an ohmic conductor is directly proportional to its applied potential difference:

$$\frac{V}{I} = R = \text{constant}.$$

Its V -versus- I graph is consequently a straight line through the origin. A non-ohmic device can still have a value of V/I assigned at each nonzero operating current without obeying this constant-ratio law.

Step 4: (ii) Read the polarities and find the open-circuit voltage In the printed figure, both cells have their long positive plate toward A and their negative plate toward B. Put $V = V_A - V_B$, and take each branch current as positive when it flows internally from B toward A. For the two branches,

$$I_1 = \frac{\mathcal{E}_1 - V}{r_1}, \quad I_2 = \frac{\mathcal{E}_2 - V}{r_2}.$$

With the external terminals open, no current leaves A, so $I_1 + I_2 = 0$. The common terminal voltage, which is the equivalent emf, is therefore

$$\begin{aligned} \mathcal{E}_{\text{eq}} &= \frac{\mathcal{E}_1/r_1 + \mathcal{E}_2/r_2}{1/r_1 + 1/r_2} \\ &= \frac{12/1 + 6/0.5}{1/1 + 1/0.5} \text{ V} \\ &= \frac{24}{3} \text{ V} = 8 \text{ V}. \end{aligned}$$

This positive value means that A is at the higher potential. As a check, the unequal emfs drive an internal circulating current $(12 - 6)/(1 + 0.5) = 4 \text{ A}$. The branch voltages agree: $12 - 4(1) = 8 \text{ V}$ and $6 + 4(0.5) = 8 \text{ V}$.

Step 5: (ii) Combine the internal resistances Replace each ideal emf by a short circuit to find the internal resistance of the equivalent source. The two original internal resistances then lie in parallel between A and B. Hence

$$\begin{aligned} r_{\text{eq}} &= \frac{r_1 r_2}{r_1 + r_2} \\ &= \frac{1 \times 0.5}{1 + 0.5} \Omega \\ &= \frac{1}{3} \Omega. \end{aligned}$$

This value is smaller than either individual resistance, as expected for a parallel combination.

Step 6: Conclusion Rapid field propagation starts local electron drift throughout the circuit; a high-current, low-voltage source needs small internal resistance to avoid a large internal voltage drop; and Ohm's law requires the ratio V/I to remain constant under fixed physical conditions. For the cells

shown,

$$\mathcal{E}_{\text{eq}} = 8 \text{ V}, \quad r_{\text{eq}} = \frac{1}{3} \Omega \approx 0.33 \Omega,$$

with A as the positive terminal relative to B.

Quick Tip to Solve: Check the cell polarities before using the parallel-source formula. Weight each emf by its conductance $1/r$; the smaller internal resistance gives that cell's emf more influence on the common voltage.