Past-paper walk-through

Resistance, Resistivity, and Ohm's Law ▪ 11.3

eXercise

Questions in this set

- 2025 Q2
- 2025 Q3
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Reading the mark scheme

- **B1** a mark that stands on its own – the point is either made or not.
- **M1** a *method* mark: the right approach, even if the number is wrong.
- **A1** an *answer* mark, and it usually needs its M mark first.
- **C1** a working mark on the way to the answer.
- // separates answers the examiner accepts equally.
- **ecf** = error carried forward: a later part is marked on your own earlier answer.
- **owtte** = "or words to that effect" – the wording need not match.

Question 2

2025 ▪ Q2

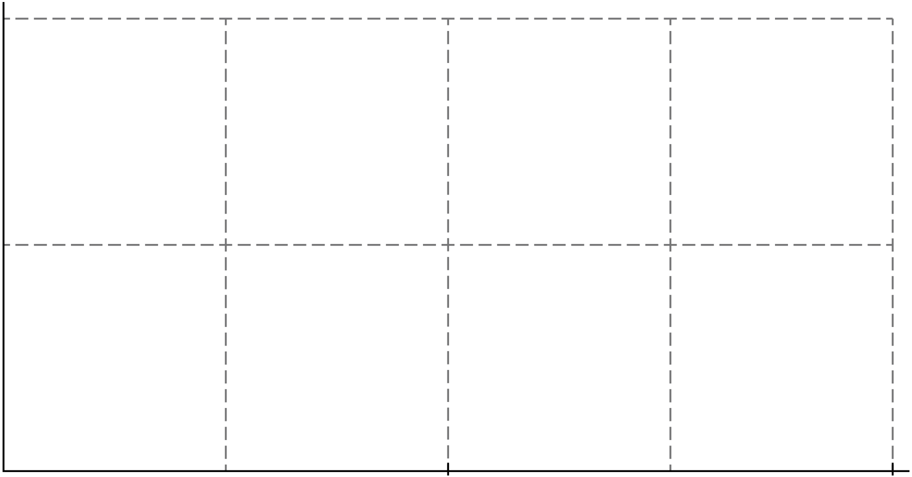
A rotating, circular, conducting loop of area A and resistance R is in an external uniform magnetic field of magnitude B that is directed in the $-z$-direction. At time $t = 0$, the magnetic field is perpendicular to the plane of the loop, as shown in Figure 1. The loop is rotating with constant angular speed ω and period T about the dashed line that is along the diameter of the loop. The value of the magnetic flux through the loop as a function of time t is $\Phi = BA\cos(\omega t)$.
[Figure 1: A circular loop shown face-on with uniform magnetic field B (into the page, shown by an array of $\times$ symbols) filling the region around and through the loop. A dashed vertical line along a diameter of the loop is the rotation axis, with angular velocity ω indicated by a curved arrow at the top. A small 3D axis to the right shows $+y$ up, $+x$ to the right, and $+z$ out of the page (circle with a dot).]

Question 2

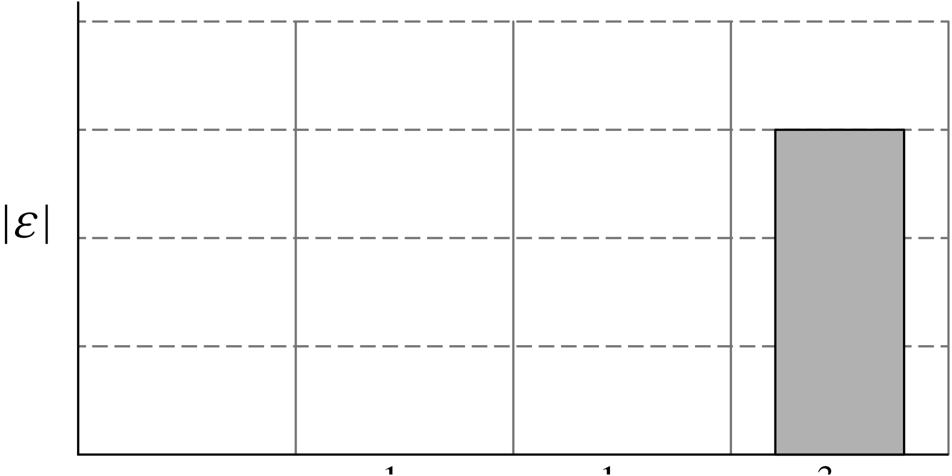
(a) The absolute value of the induced emf in the loop is $|\varepsilon|$. The partially completed bar chart in Figure 2 shows a bar that represents $|\varepsilon|$ at $t = \dfrac{3}{4}T$. In Figure 2, **draw** bars to represent $|\varepsilon|$ at times $t = 0$, $\dfrac{1}{4}T$, and $\dfrac{1}{2}T$ relative to $|\varepsilon|$ shown at $\dfrac{3}{4}T$. If $|\varepsilon| = 0$, **write** a "0" in that column.

[Figure 2: A bar chart with vertical axis $|\varepsilon|$ and horizontal axis showing four columns labeled $t = 0$, $\frac{1}{4}T$, $\frac{1}{2}T$, $\frac{3}{4}T$. Only the $\frac{3}{4}T$ column already has a bar drawn, reaching to a height roughly midway up the chart; the other three columns are blank for the student to fill in.]

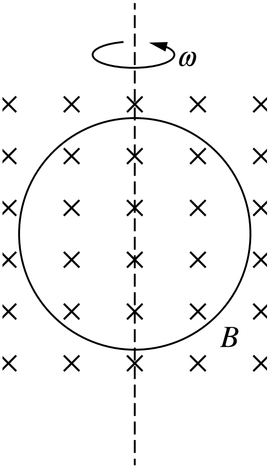
Question 2



Question 2



Question 2



Question 2

2025 ▪ Q2

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Question 2

(b) Derive an expression for the maximum induced current in the loop in terms of A, R, B, ω, and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

Question 2

2025 ▪ Q2

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Question 2

(c) On the axes shown in Figure 3, **sketch** a graph of the instantaneous power P dissipated by the loop as a function of t during the time interval $0 \leq t \leq T$.
[Figure 3: A blank set of axes with vertical axis labeled P and horizontal axis labeled t, origin O. Two vertical dashed reference lines are marked on the t-axis at positions labeled $\frac{1}{2}T$ and T.]

Question 2

2025 ▪ Q2

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Question 2

(d) Indicate whether the sketch you drew in part C is or is not consistent with the bars that you drew in part A. Briefly **justify** your answer by referencing the functional dependence between P and $|\varepsilon|$.

Solution 2

(a)

Mark scheme

- The bar chart shows $|\varepsilon| att = 3/4 Talreadydrawn(height3units).Draw: abaratt = 1/4 Twithheight3units(equaltothegiven3/4 Tbar), andwrite'0' att = 0andatt = 1/2 T(|\varepsilon| iszeroatthosetimes, when \cos(\omega t) isatanextremumsoitsderivative - -theemf - -iszero).Points: (1) abarat1/4 T, (2) thatbarhasheight3units(matchingthe3/4 Tbar$
$0att = 0andt = 1/2 T.$

Solution 2

(b) Mark scheme

- Start from Faraday's law: $\varepsilon = -\frac{d\Phi_B}{dt}(signnotrequired).With\Phi_B = BA\cos(\omega t), \varepsilon = -\frac{d}{dt}[BA\cos(\omega t)] = BA\omega\sin(\omega t), so\varepsilon_{max} = BA\omega.UsingOhm'slaw, I = \varepsilon/R(orI = \Delta V/Rwith\Delta V = \varepsilon), soI_{max} = \varepsilon_{max}/R = \frac{BA\omega}{R}.Points:(1)writing\varepsilon = -d\Phi_B/dt,(2)correctexpressionforinducedemf\varepsilon = BA\omega\sin(\omega t),(3)usingOhm'slawI = \varepsilon/R,(4)correctexpressionforthemaximuminducedcurrentI_{max} = BA\omega/R.$

Solution 2

(c) Mark scheme

- Sketch P vs t (power dissipated, P $\propto \varepsilon^2 \propto \sin^2(\omega t)$) : $anapproximatelysinusoidalcurve(allhumpsabovetheaxis, sincepowerisnevernegative)thatcomplet$
$0 andt = T(since \sin^2 hashalftheperiodof \sin), startingattheorigin(P = 0 att =$
$0) withequalmaximumvaluesandequalminimumvalues(minimaatP = 0, occurringatt =$
$0, T/2, T; maximamidwaybetween). AcurvethatstartsandendsatP =$
$0 withasinglemaximumcanalsoearnthethirdpoint. Points :$
$(1) approximatelysinusoidalcurve, (2) exactlytwocyclesshownover 0 to T, (3) startsattheoriginwithe$

Solution 2

(d)

Mark scheme

- Yes, the graph in part C is consistent with the bars drawn in part A. Because P is proportional to $\varepsilon^2, Pismaximumwhenever|\varepsilon|ismaximum(att = 1/4Tand3/4T)andPiszero(minimum)whenever\varepsilon iszero(att = 0and1/2T) - -i.e., themaxima/minimaofthepart - CgraphalignwiththebarsofpartA.Points : (1)correctlystatingtherepresentationsareconsistent, (2)correctjustificationreferencingthatPisp$

Question 3

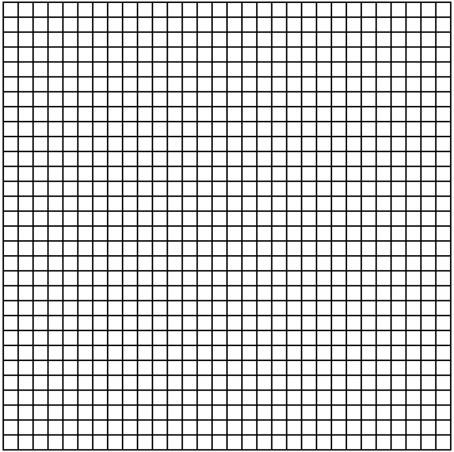
2025 ▪ Q3

In Experiment 1, students are asked to use a graph to determine the resistivity ρ_1 of a circuit element that is connected to a variable power supply, as shown in Figure 1. The circuit element is cylindrical and has uniform resistivity. The students have access to a voltmeter, an ammeter, and a ruler.

[Figure 1: A simple circuit diagram — a rectangular loop containing a variable power supply (battery symbol with an arrow through it, indicating adjustable voltage) at the top, connected by wires down both sides to a cylindrical circuit element (shown as a shaded rectangular bar) at the bottom, labeled "Circuit Element".]

(a) Describe a procedure for collecting data that would allow the students to use a graph to determine ρ_1, including any steps necessary to reduce experimental uncertainty.

Question 3



Question 3

L (m)	R (Ω)
0.010	0.90
0.020	1.6
0.030	2.5
0.040	3.2
0.050	4.0

Question 3

2025 ▪ Q3

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(b) Describe how the collected data could be graphed and how that graph would be analyzed to determine ρ_1.

Question 3

2025 ▪ Q3

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(c) In Experiment 2, the students are asked to use a graph to determine the resistivity ρ_2 of solid, cylindrical resistors made of the same material but of different lengths L. The cross-sectional area of each resistor is 5.0×10^{-6} m^2. The students directly

Question 3

measure the resistance R between the ends of each resistor. Table 1 provides L and R for each resistor.

Table 1

L (m)	R (Ω)
0.010	0.90
0.020	1.6
0.030	2.5
0.040	3.2
0.050	4.0

(c)(i) Indicate two quantities, either measured quantities from Table 1 or additional calculated quantities, that could be graphed to produce a straight line that could be used to determine ρ_2.

Vertical axis: ________ Horizontal axis: ________

(c)(ii) On the grid provided, create a graph of the quantities indicated in part C (i).

- Use Table 2 to record the measured or calculated quantities that you will plot.
- Clearly **label** the axes, including units as appropriate.

Question 3

- **Plot** the points you recorded in Table 2.

[Figure: A blank square grid (graph paper) for plotting the data.]

(c)(iii) Draw a best-fit line for the data graphed in part C (ii).

Question 3

2025 ▪ Q3

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[Figure 1: A simple circuit diagram — a rectangular loop containing a variable power supply (battery symbol with an arrow through it, indicating adjustable voltage) at the top, connected by wires down both sides to a cylindrical circuit element (shown as a shaded rectangular bar) at the bottom, labeled "Circuit Element".]

(d) Using the best-fit line that you drew in part C (iii), **calculate** an experimental value for ρ_2.

Solution 3

(a) Mark scheme

- Procedure: Measure the length and diameter of the circuit element; use the diameter to calculate its cross-sectional area. Measure the current in the circuit element. Repeat the procedure, taking multiple current measurements and/or varying the potential difference of the power supply across several settings, to reduce experimental uncertainty. Points: (1) a procedure that measures the element's length and current and determines its cross-sectional area, (2) a procedure that reduces experimental uncertainty (e.g., repeated current measurements, or varying the supply potential difference).

Solution 3

(b) Mark scheme

- Graph the potential difference across the circuit element as a function of the current in the circuit element (or the reciprocal relationship); this is consistent with V $= (\rho_1\ell/(\pi r^2))I, astraightlinethroughtheorigin.Usetheslopeofthegraph, whichequals\rho_1\ell/(\pi r^2)(\ell = length, r = radiusofthecircuitelement), togetherwiththemeasured\ell andr, todetermine\rho_1.Points: (1)indicatingquantitiesthatcanbeappropriatelygraphedtodetermine\rho_1, consistentwiththepart-Aprocedure, (2)acorrectanalysisofthatgraph(identifyingtheslopeas\rho_1\ell/(\pi r^2)andsolvingfor\rho_1).$

Solution 3

(c)

Mark scheme

- This is the introductory stem for Part C (Experiment 2): resistors of cross-sectional area 5.0×10^{-6} $m^2 anddifferentlengthsL; themeasuredresistanceRforeachisgiveninTable1.Itstatesth$ $-allPartCpointsarescoredinsub-partsC(i)-C(iii)(andpartDusestheresultinggraph).$

Solution 3

(c)(i)

Mark scheme

- Since R $= \rho_2 L/A with A fixed, plot R(vertical axis) as a function of L(horizontal axis, or the reciproca$
$axis assignment) to produce a straight line through the origin whose slope is \rho_2/A.(Other equivalent qu$
$indicating appropriate quantities(e.g., R vs L) that could be graphed to produce a straight line usable t$

Solution 3

(c)(ii) Mark scheme

- Plot R
  (Ω)*ontheverticalaxisandL*(m)*onthehorizontalaxis*, *bothaxeslabeledwithunitsandalinearscale*$($*e.g.*
  (1)*correctlylabeledaxeswithunitsonalinearscale*, (2)*datapointscorrectlyplottedconsistentwiththe*

Solution 3

(c)(iii)

Mark scheme

- Draw a single straight best-fit line through the plotted R-vs-L data points (a line that reasonably follows the trend of the points rather than connecting them dot-to-dot). Point: for drawing a best-fit line/curve that approximates the trend of the plotted data.

Solution 3

(d)

Mark scheme

- Read the slope of the best-fit line, e.g. slope $= \Delta R/\Delta L = (4.0\ \Omega - 2.0\ \Omega)/(0.050\ m - 0.024\ m) = 77\ \Omega/m. Since R = \rho_2 L/A = (\rho_2/A)L, theslopeequals \rho_2/A, so \rho_2 = A \cdot \text{(slope)} = (5.0 \times 10^{-6}\ m^2)(77\ \Omega/m) \approx 3.9 \times 10^{-4}\ \Omega \cdot m. Points: (1) correctlyrelatingtheslopeofthebest-fitlineto \rho_2 via R = \rho_2 L/A, (2) aresultingvalueof \rho_2 between 3.5 \times 10^{-4} and 4.5 \times 10^{-4}\ \Omega \cdot m (creditisforavalueinthisrange, consistentwiththestudent's owngraph).$

Question 2

2024 Set 2 ▪ Q2

[Figure 1: A circuit diagram. A battery of emf $\mathcal{E}$ is on the left side of the loop. Along the top wire, moving right from the battery, is a switch, then resistor R_A, then resistor R_B (both drawn as zigzag resistor symbols). The right side of the loop contains an inductor of inductance L (drawn as a coil symbol), connecting back down to the battery, completing the rectangular circuit loop.]

Students are asked to determine the resistance R of identical resistors R_A and R_B. The resistors are connected in series with each other, a battery of known emf $\mathcal{E}$, an inductor of known inductance L, and a switch, as shown in Figure 1. The students have access to a voltmeter that can measure potential difference as a function of time. The students are required to measure a quantity that increases with time to determine R.

Question 2

(a)(i) On the circuit diagram shown in Figure 1, **draw** the voltmeter, using the following symbol, with connections that would allow the students to correctly measure a potential difference that increases with time.
[Voltmeter Symbol: a circle containing the letter “V”, with a wire lead extending from each side, labeled “Voltmeter Symbol”.]
(a)(ii) Describe a procedure for collecting data that would allow the students to graphically determine the experimental value for R using a measured quantity that increases with time. Provide enough detail so that another student could replicate the experiment.

long time, the absolute value of the potential difference across R_A is $|\Delta V_2|$.

(d) **Indicate** whether $|\Delta V_2|$ is greater than, less than, or equal to $|\Delta V_1|$.

_____ $|\Delta V_2| > |\Delta V_1|$ _____ $|\Delta V_2| < |\Delta V_1|$ _____ $|\Delta V_2| = |\Delta V_1|$

Justify your answer.

Question 2

Figure 2

Question 2

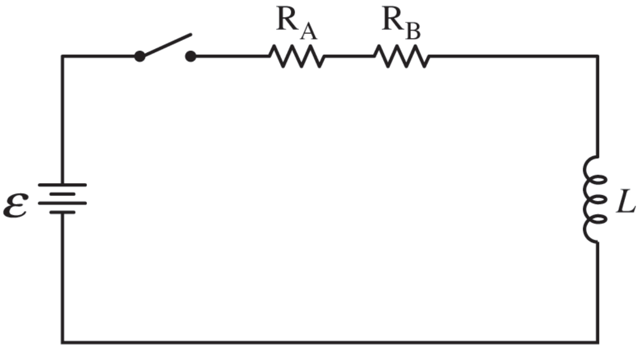

Figure 1

Question 2

2024 Set 2 ▪ Q2

[Figure 1: A circuit diagram. A battery of emf $\mathcal{E}$ is on the left side of the loop. Along the top wire, moving right from the battery, is a switch, then resistor R_A, then resistor R_B (both drawn as zigzag resistor symbols). The right side of the loop contains an inductor of inductance L (drawn as a coil symbol), connecting back down to the battery, completing the rectangular circuit loop.]

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(b)(i) On the axes shown in Figure 2, produce a graph that represents the expected trend of the data by completing the following tasks.

Question 2

- **Label** the quantities graphed on the vertical and horizontal axes.
- **Sketch** a line or curve that represents the expected trend of the collected data.
- **Label** any appropriate intercepts and/or asymptotes in terms of the quantities provided.

[Figure 2: A blank graph with a vertical axis (upward arrow, unlabeled) and a horizontal axis (rightward arrow, unlabeled, drawn dashed). No scale or curve shown; axes are empty for the student to label and sketch.]

(b)(ii) Describe how the information from the graph in part (b)(i) would be used to determine the experimental value for R.

Question 2

2024 Set 2 ▪ Q2

[Figure 1: A circuit diagram. A battery of emf $\mathcal{E}$ is on the left side of the loop. Along the top wire, moving right from the battery, is a switch, then resistor R_A, then resistor R_B (both drawn as zigzag resistor symbols). The right side of the loop contains an inductor of inductance L (drawn as a coil symbol), connecting back down to the battery, completing the rectangular circuit loop.]

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(c) Starting with an appropriate application of Kirchhoff's loop rule, **derive**, but do NOT solve, a differential equation that can be used to determine the current I in the

Question 2

inductor at time t after the switch is closed. Express your answer in terms of R, $\mathcal{E}$, L, t, and physical constants, as appropriate.

Question 2

2024 Set 2 ▪ Q2

[Figure 1: A circuit diagram. A battery of emf $\mathcal{E}$ is on the left side of the loop. Along the top wire, moving right from the battery, is a switch, then resistor R_A, then resistor R_B (both drawn as zigzag resistor symbols). The right side of the loop contains an inductor of inductance L (drawn as a coil symbol), connecting back down to the battery, completing the rectangular circuit loop.]

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(d) After reaching steady state, the absolute value of the potential difference across R_A is $|\Delta V_1|$. The students replace the original inductor with a new inductor that has

Question 2

nonnegligible resistance. The experiment is repeated. After a long time, the absolute value of the potential difference across R_A is $|\Delta V_2|$.

Indicate whether $|\Delta V_2|$ is greater than, less than, or equal to $|\Delta V_1|$.

$|\Delta V_2| > |\Delta V_1|$ $|\Delta V_2| < |\Delta V_1|$ $|\Delta V_2| = |\Delta V_1|$

Justify your answer.

Solution 2

(a)(i)

Mark scheme

- Place the voltmeter in parallel with Resistor A, Resistor B, or the series combination of Resistors A and B (not across the inductor) — this location's potential difference increases with time as current builds up after the switch closes, unlike the inductor voltage which decreases with time. 1 point for correctly placing the voltmeter across one of these three valid options.

Solution 2

(a)(ii)

Mark scheme

- Procedure: Close the switch, then use the voltmeter to record the potential difference across the chosen resistor(s) as a function of time, from immediately after the switch is closed until steady-state conditions are established (or until enough time has elapsed that the time constant can be determined from the data). 1 point for a procedure indicating the voltmeter is used to measure the potential difference for at least one time, 1 point for measuring from immediately after the switch closes through steady state (or until the time constant is determinable).

Solution 2

(b)(i) Mark scheme

- Sketch potential difference (vertical axis) vs. time (horizontal axis): a curve that starts at the origin $(0, 0)$, is concave-down and increasing, and asymptotically approaches a nonzero potential-difference value. The labeled horizontal asymptote must be consistent with the voltmeter placement chosen in part (a)(i) — e.g. $\varepsilon/2$ if measuring across one resistor (A or B alone), or ε if measuring across the series combination of A and B. 1 point for correctly labeling potential difference vertically and time horizontally, 1 point for a concave-down increasing curve, 1 point for a curve starting at the origin and asymptotically approaching a nonzero value, 1 point for correctly labeling the horizontal asymptote consistent with part (a)(i).

Solution 2

(b)(ii) Mark scheme

- Fit the data to an exponential function of the form $V_R = \varepsilon\left(1 - e^{-t\,2R/L}\right)$ (for the series-combination case; for a single resistor the analogous form applies). Since ε and L are known, the coefficient multiplying t in the fit equals $2R/L$, from which R can be calculated. Alternate: read off the time at which the potential difference reaches $\approx 0.63\varepsilon/2$ (one resistor) or $\approx 0.63\varepsilon$ (combination); this time equals the time constant $L/2R$, and since L is known, R can be calculated. 1 point for indicating the curve fit is an exponential function (or, alternately, indicating the 0.63-value time), 1 point for indicating the fitted coefficient of t equals $2R/L$ (or, alternately, that the time constant equals $L/2R$).

Solution 2

(c) Mark scheme

- Apply Kirchhoff's loop rule: $\varepsilon - \Delta V_R - \Delta V_L = 0$. The potential difference across the series combination of the two resistors is $I(2R)$, and the magnitude of the potential difference across the inductor is $L\,dI/dt$. Substituting: $\varepsilon - I(2R) - L\dfrac{dI}{dt} = 0$, which rearranges to $\dfrac{dI}{dt} = \dfrac{\varepsilon}{L} - \dfrac{2IR}{L} = -\dfrac{R}{L}\left(2I - \dfrac{\varepsilon}{R}\right)$ (do not solve further). 1 point for a multi-step derivation beginning with an attempt at Kirchhoff's loop rule, 1 point for indicating the resistor-combination potential difference is $I(2R)$, 1 point for indicating the inductor's potential-difference magnitude is $L\,dI/dt$.

Solution 2

(d) Mark scheme

- $|\Delta V_2| < |\Delta V_1|$. Justification: because the new inductor has nonnegligible resistance, the total resistance of the new circuit is greater than in the original circuit, so at steady state the current is smaller than before, and the potential difference across R_A (which equals IR_A) decreases. (Equivalently: the increased total resistance means more of the source emf is dropped across the inductor's internal resistance at steady state, increasing the potential difference across the inductor and thereby decreasing the potential difference across R_A.) 1 point for selecting $|\Delta V_2| < |\Delta V_1|$ with an attempted justification, 1 point for indicating the total resistance has increased, 1 point for indicating the current decreases due

Solution 2

to the increased resistance (or, alternately, that the inductor's potential difference increases so R_A's must decrease).

Question 3

2022 Set 1 ▪ Q3

A lightbulb of resistance $R = 10.0\ \Omega$ is connected to a rectangular loop of wire of negligible resistance near a very long current-carrying wire. The rectangular loop has a length $L = 4.0$ cm and a width $W = 2.0$ cm and is positioned so one of the longer sides of the loop is a distance $d = 1.0$ cm above and parallel to the long wire, as shown. The current in the long wire is initially flowing to the right and is given by $I(t) = C - Dt$, where $C = 10.0$ A and $D = 2.0$ A/s. At time $t = 5.0$ s, the current in the long wire is instantaneously zero as the current changes direction.
[Diagram: a rectangular loop of wire with a lightbulb (circle with X inside) in the top wire of the loop, labeled $R = 10.0\ \Omega$. The loop has width $W = 2.0$ cm (vertical side) and length $L = 4.0$ cm (horizontal side). Below the loop, a long horizontal wire carries current $I(t)$ to the right (arrow labeled $I(t)$ at the right end), separated from the bottom of the loop by a distance $d = 1.0$ cm.]

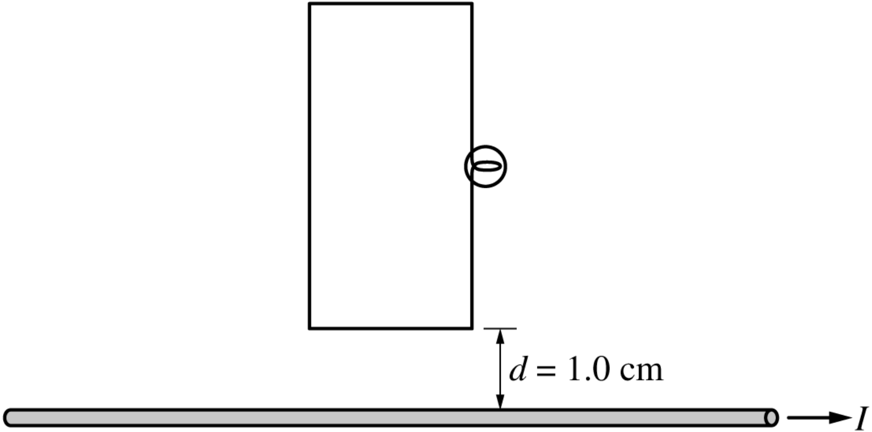
Question 3

(a) What is the direction, if any, of the magnetic field produced by the induced current in the rectangular loop as the current in the long wire changes direction?

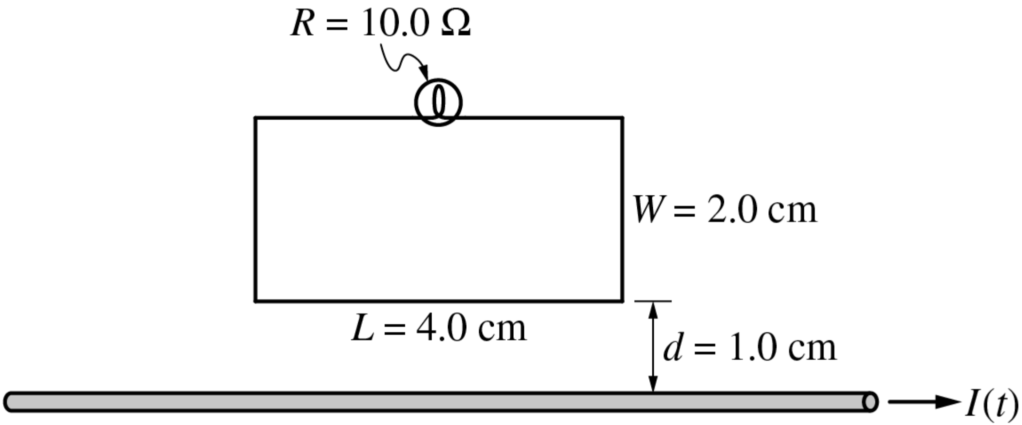
____ Into the page ____ Out of the page ____ No direction, because the field is zero

Justify your answer.

Question 3



Question 3



Question 3

2022 Set 1 ▪ Q3

A lightbulb of resistance $R = 10.0\ \Omega$ is connected to a rectangular loop of wire of negligible resistance near a very long current-carrying wire. The rectangular loop has a length $L = 4.0$ cm and a width $W = 2.0$ cm and is positioned so one of the longer sides of the loop is a distance $d = 1.0$ cm above and parallel to the long wire, as shown. The current in the long wire is initially flowing to the right and is given by $I(t) = C - Dt$, where $C = 10.0$ A and $D = 2.0$ A/s. At time $t = 5.0$ s, the current in the long wire is instantaneously zero as the current changes direction.

[Diagram: a rectangular loop of wire with a lightbulb (circle with X inside) in the top wire of the loop, labeled $R = 10.0\ \Omega$. The loop has width $W = 2.0$ cm (vertical side) and length $L = 4.0$ cm (horizontal side). Below the loop, a long horizontal wire carries current $I(t)$ to the right (arrow labeled $I(t)$ at the right end), separated from the bottom of the loop by a distance $d = 1.0$ cm.]

Question 3

(b) Calculate the magnetic flux through the loop due to only the long wire at time $t = 3.0$ s.

Question 3

2022 Set 1 ▪ Q3

A lightbulb of resistance $R = 10.0\ \Omega$ is connected to a rectangular loop of wire of negligible resistance near a very long current-carrying wire. The rectangular loop has a length $L = 4.0$ cm and a width $W = 2.0$ cm and is positioned so one of the longer sides of the loop is a distance $d = 1.0$ cm above and parallel to the long wire, as shown. The current in the long wire is initially flowing to the right and is given by $I(t) = C - Dt$, where $C = 10.0$ A and $D = 2.0$ A/s. At time $t = 5.0$ s, the current in the long wire is instantaneously zero as the current changes direction.

[Diagram: a rectangular loop of wire with a lightbulb (circle with X inside) in the top wire of the loop, labeled $R = 10.0\ \Omega$. The loop has width $W = 2.0$ cm (vertical side) and length $L = 4.0$ cm (horizontal side). Below the loop, a long horizontal wire carries current $I(t)$ to the right (arrow labeled $I(t)$ at the right end), separated from the bottom of the loop by a distance $d = 1.0$ cm.]

Question 3

(c) Calculate the current through the lightbulb at time $t = 3.0$ s.

Question 3

2022 Set 1 ▪ Q3

A lightbulb of resistance $R = 10.0\ \Omega$ is connected to a rectangular loop of wire of negligible resistance near a very long current-carrying wire. The rectangular loop has a length $L = 4.0$ cm and a width $W = 2.0$ cm and is positioned so one of the longer sides of the loop is a distance $d = 1.0$ cm above and parallel to the long wire, as shown. The current in the long wire is initially flowing to the right and is given by $I(t) = C - Dt$, where $C = 10.0$ A and $D = 2.0$ A/s. At time $t = 5.0$ s, the current in the long wire is instantaneously zero as the current changes direction.

[Diagram: a rectangular loop of wire with a lightbulb (circle with X inside) in the top wire of the loop, labeled $R = 10.0\ \Omega$. The loop has width $W = 2.0$ cm (vertical side) and length $L = 4.0$ cm (horizontal side). Below the loop, a long horizontal wire carries current $I(t)$ to the right (arrow labeled $I(t)$ at the right end), separated from the bottom of the loop by a distance $d = 1.0$ cm.]

Question 3

(d) A group of students attempts to experimentally verify whether the current through the lightbulb is consistent with the current calculation from part (c). The current in the rectangular loop is measured to be greater than the current calculated in part (c). Which of the following could explain this discrepancy? Select one answer.
____ The students did not account for Earth's magnetic field. ____ The rectangular loop is tilted and is not in the same plane as the wire. ____ The resistance of the lightbulb is greater than the recorded value. ____ The long side of the rectangular loop is shorter than the recorded value. ____ The current in the long wire changes at a faster rate than expected.
Briefly justify your answer.

Question 3

2022 Set 1 ▪ Q3

A lightbulb of resistance $R = 10.0\ \Omega$ is connected to a rectangular loop of wire of negligible resistance near a very long current-carrying wire. The rectangular loop has a length $L = 4.0$ cm and a width $W = 2.0$ cm and is positioned so one of the longer sides of the loop is a distance $d = 1.0$ cm above and parallel to the long wire, as shown. The current in the long wire is initially flowing to the right and is given by $I(t) = C - Dt$, where $C = 10.0$ A and $D = 2.0$ A/s. At time $t = 5.0$ s, the current in the long wire is instantaneously zero as the current changes direction.

[Diagram: a rectangular loop of wire with a lightbulb (circle with X inside) in the top wire of the loop, labeled $R = 10.0\ \Omega$. The loop has width $W = 2.0$ cm (vertical side) and length $L = 4.0$ cm (horizontal side). Below the loop, a long horizontal wire carries current $I(t)$ to the right (arrow labeled $I(t)$ at the right end), separated from the bottom of the loop by a distance $d = 1.0$ cm.]

Question 3

(e) Later, the same rectangular loop with lightbulb is rotated such that a short side of the loop is 1.0 cm above and parallel to the long current-carrying wire, as shown. The current in the wire is again initially flowing from left to right and given by $I(t) = C - Dt$, where $C = 10.0$ A and $D = 2.0$ A/s. The current through the lightbulb in the loop's new orientation at time $t = 3.0$ s is I_2. Which of the following correctly relates the I_2 to I_1, the current through the lightbulb in part (c)?
[Diagram: a tall rectangular loop of wire oriented vertically, with a lightbulb (circle with X inside) partway up the loop. Below the loop, a long horizontal wire carries current to the right (arrow labeled I at the right end), with the short side of the loop positioned a distance $d = 1.0$ cm above and parallel to the wire.]
$\mathrm{I}_2 < I_1$ $\mathrm{I}_2 = I_1$ $\mathrm{I}_2 > I_1$
Justify your answer.

Solution 3

(a) Mark scheme

- Answer: Out of the page (1 pt, for the correct selection with an attempt at relevant justification). As the current in the long straight wire decreases toward zero (changing direction), the magnetic field it produces through the loop — originally directed out of the page — is decreasing in magnitude (1 pt: justification correctly relates the changing current in the wire to the changing flux through the loop with respect to time). By Lenz's law, the induced current opposes this decrease, so it produces its own magnetic field directed out of the page through the loop to compensate for the decreasing flux (1 pt: indicating the induced current opposes the change in flux).

Solution 3

(b) Mark scheme

- $\Phi_B = \int \vec{B} \cdot d\vec{A}$ (1 pt: appropriate integral equation with a substitution for the magnetic field, to calculate flux). The field from the long wire is $B = \dfrac{\mu_0 I}{2\pi r}$ (1 pt: correct equation for B as a function of distance from the wire). At $t = 3$ s, with $I(t) = C - Dt$, $C = 10.0$ A, $D = 2.0$ A/s: $I(3\text{ s}) = 10\text{ A} - (2\text{ A/s})(3\text{ s}) = 4$ A (1 pt: substituting $t = 3$ s to find the current). Integrating across the loop (near edge a distance $d = 0.01$ m from the wire, far edge at $d + W = 0.03$ m, length $L = 0.04$ m along the wire): $\Phi_B = \displaystyle\int_d^{d+W} \frac{\mu_0 IL}{2\pi r}\, dr = \frac{\mu_0 IL}{2\pi} \ln\left[\frac{d+W}{d}\right]$ (1 pt:

Solution 3

integrating B with correct limits and a correct substitution for dA). Numerically:

$$\Phi_B = \frac{(4\pi \times 10^{-7}\ \mathsf{T \cdot m/A})(4\ \mathsf{A})(0.04\ \mathsf{m})}{2\pi} \ln\left[\frac{0.03\ \mathsf{m}}{0.01\ \mathsf{m}}\right] = 3.52 \times 10^{-8}\ \mathsf{T \cdot m}^2.$$

Solution 3

(c) Mark scheme

- $\varepsilon = \left|\frac{d\Phi}{dt}\right|$ (1 pt: using Faraday's law to determine the emf across the lightbulb). With $\Phi_B = \frac{\mu_0(C - Dt)L}{2\pi}\ln\left[\frac{d+W}{d}\right]$, differentiating (only $I(t) = C - Dt$ depends on t, with $dI/dt = -D$): $\varepsilon = \frac{\mu_0 DL}{2\pi}\ln\left[\frac{d+W}{d}\right]$. Then $I = \frac{\varepsilon}{R} = \frac{\mu_0 DL}{2\pi R}\ln\left[\frac{d+W}{d}\right]$ (1 pt: using Ohm's law to find the current consistent with the emf just found). Substituting $D = 2.0$ A/s, $L = 0.04$ m, $R = 10\ \Omega$:

Solution 3

$I = \frac{(4\pi \times 10^{-7}\ \mathrm{T \cdot m/A})(2.0\ \mathrm{A/s})(0.04\ \mathrm{m})}{2\pi(10\ \Omega)} \ln\left[\frac{0.03}{0.01}\right] = 1.8 \times 10^{-9}$ A (1 pt: correct substitution of dI/dt and R).

Solution 3

(d)

Mark scheme

- Answer: The current in the long wire changes at a faster rate than expected (1 pt for the correct selection; the justification point cannot be earned with an incorrect selection). Justification: if the current in the wire changes at a faster rate, there is a greater rate of change of magnetic flux through the loop, so the induced emf — and hence the induced current through the lightbulb — will be higher than the calculated value, consistent with the measured current being greater than the part (c) calculation (1 pt).

Solution 3

(e) Mark scheme

- Answer: $I_2 < I_1$ (1 pt, for the correct selection with an attempt at relevant justification). In the new orientation (a short side of the loop 1.0 cm above and parallel to the wire), some parts of the rectangular loop are farther from the straight wire than in the original orientation, so the total magnetic flux through the loop is smaller (1 pt: indicating the total flux in the loop is less in the new orientation). Since the rate of change of the flux has the same distance-dependence as the flux itself, the rate of change of flux — and therefore the induced emf and current — will also be smaller, so $I_2 < I_1$ (1 pt: correctly relating the rate of change of flux to the total flux inside the loop).

Question 3

2022 Set 2 ▪ Q3

[Side View: a solenoid drawn as a coil of wire with current $I(t)$ entering at the left, labeled "Solenoid"; a single circular "Loop of Wire" is shown positioned partway along/around the solenoid's axis, oriented with its plane perpendicular to the solenoid's axis.] [End View: the solenoid seen end-on as a circle, with a smaller concentric circle labeled "Loop of Wire" carrying current $I(t)$ shown with a circular arrow indicating direction.] [Note: Figures not drawn to scale.]

A single loop of wire with resistance $3.0\ \Omega$ and radius 0.10 m is placed inside a solenoid, with the normal to the loop parallel to the axis of the solenoid. The solenoid has 500 turns, is 0.25 m long, and is connected to a power supply that is not shown. At time $t = 0$, the power supply is turned on, and the current I in the solenoid as a function of t is given by the equation $I(t) = \beta t$, where $\beta = 5.0$ A/s. The direction of the current in the solenoid is clockwise, as shown in the end view.

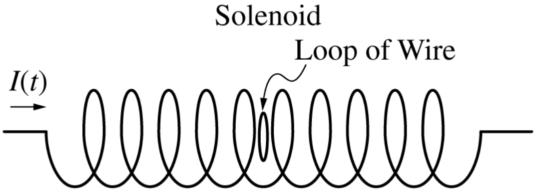
Question 3

(a) At time $t = 2.0$ s, is the induced current in the loop, as seen from the end view shown, clockwise, counterclockwise, or zero?

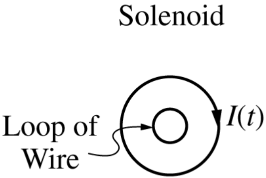
$C^{lockwise}{}_{C}{}^{ounterclockwise}{}_{Z}{}^{ero}$

Justify your answer.

Question 3



Side View



End View

Note: Figures not drawn to scale.

Question 3

2022 Set 2 ▪ Q3

[Side View: a solenoid drawn as a coil of wire with current $I(t)$ entering at the left, labeled "Solenoid"; a single circular "Loop of Wire" is shown positioned partway along/around the solenoid's axis, oriented with its plane perpendicular to the solenoid's axis.] [End View: the solenoid seen end-on as a circle, with a smaller concentric circle labeled "Loop of Wire" carrying current $I(t)$ shown with a circular arrow indicating direction.] [Note: Figures not drawn to scale.]

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Question 3

(b) Calculate the current in the loop of wire at time $t = 2.0$ s.

Question 3

2022 Set 2 ▪ Q3

[Side View: a solenoid drawn as a coil of wire with current $I(t)$ entering at the left, labeled "Solenoid"; a single circular "Loop of Wire" is shown positioned partway along/around the solenoid's axis, oriented with its plane perpendicular to the solenoid's axis.] [End View: the solenoid seen end-on as a circle, with a smaller concentric circle labeled "Loop of Wire" carrying current $I(t)$ shown with a circular arrow indicating direction.] [Note: Figures not drawn to scale.]

A single loop of wire with resistance $3.0\ \Omega$ and radius 0.10 m is placed inside a solenoid, with the normal to the loop parallel to the axis of the solenoid. The solenoid has 500 turns, is 0.25 m long, and is connected to a power supply that is not shown. At time $t = 0$, the power supply is turned on, and the current I in the solenoid as a function of t is given by the equation $I(t) = \beta t$, where $\beta = 5.0$ A/s. The direction of the current in the solenoid is clockwise, as shown in the end view.

Question 3

(c) Calculate the total energy dissipated by the loop of wire from time $t = 0$ to time $t = 2.0$ s.

Question 3

2022 Set 2 ▪ Q3

[Side View: a solenoid drawn as a coil of wire with current $I(t)$ entering at the left, labeled "Solenoid"; a single circular "Loop of Wire" is shown positioned partway along/around the solenoid's axis, oriented with its plane perpendicular to the solenoid's axis.] [End View: the solenoid seen end-on as a circle, with a smaller concentric circle labeled "Loop of Wire" carrying current $I(t)$ shown with a circular arrow indicating direction.] [Note: Figures not drawn to scale.]

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Question 3

(d) A group of students attempts to verify experimentally the calculation of the current from part (b). The current in the inner circular loop at time $t = 2.0$ s is measured to be less than the current calculated in part (b). Which of the following could explain this discrepancy? Select one answer.

$T^{heexperimentdidnotaccountforEarth'smagneticfield.}{}_{T}{}^{heplaneoftheloopisnotperpendiculartotheaxisofthesolenoid.}{}_{T}{}^{hecenteroftheloopisnotontheaxisofthesolenoid.}$

m.

Justify your answer.