Past-paper walk-through

Electromagnetic Induction ▪ 13.2

eXercise

Questions in this set

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- 2025 Q2
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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 4

2026 ▪ Q4

In Scenario 1, a square conducting loop with side length s has total resistance R. The loop is held fixed in the xy-plane in an external, uniform, time-varying magnetic field that is initially directed in the $+z$-direction, as shown. The z-component of the magnetic field changes as a function of time t as described by $B_z = B_0 \cos\left(2\pi \frac{t}{t_1}\right)$, where B_0 and t_1 are positive constants.
[Figure: A grid of dots (representing a uniform magnetic field B_z pointing out of the page, in the $+z$-direction) fills the region. A square conducting loop of side length s and total resistance R is drawn within the field region, with R labeled pointing to the loop and s labeling the loop's side length via a vertical double-arrow. A small 3D axis indicator to the right shows $+y$ pointing up, $+x$ pointing right, and $+z$ pointing out of the page (circled dot).]

Question 4

(a) **Indicate** whether the induced current I in the loop is clockwise, counterclockwise, or zero during the time interval $0 < t < \frac{t_1}{4}$ by writing one of the following.
- I is clockwise. - I is counterclockwise. - I is zero.
Justify your answer without only manipulating equations.

Question 4

2026 ▪ Q4

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Question 4

(b) Derive an expression for I as a function of t in terms of s, R, B_0, t_1, t, and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

Question 4

2026 ▪ Q4

In Scenario 1, a square conducting loop with side length s has total resistance R. The loop is held fixed in the xy-plane in an external, uniform, time-varying magnetic field that is initially directed in the $+z$-direction, as shown. The z-component of the magnetic field changes as a function of time t as described by $B_z = B_0 \cos\left(2\pi \frac{t}{t_1}\right)$, where B_0 and t_1 are positive constants.

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Question 4

(c) In Scenario 2, a new square conducting loop with side length $2s$ and total resistance $2R$ is placed in the same external, uniform, time-varying magnetic field as in Scenario 1.

Indicate whether the maximum induced current I_2 in Scenario 2 is greater than, less than, or equal to the maximum induced current I_1 in Scenario 1 by writing one of the following.

- $I_2 > I_1$
- $I_2 < I_1$
- $I_2 = I_1$

Briefly **justify** your answer by referencing the expression you derived in part B.

Question 2

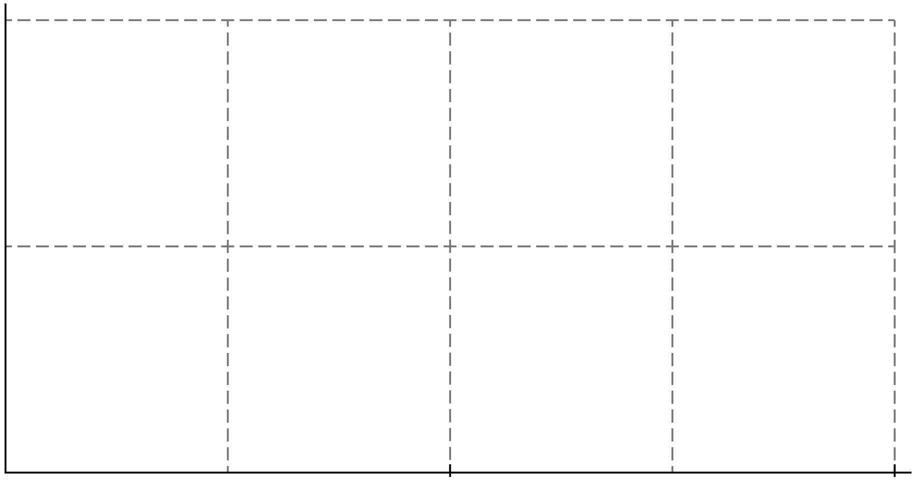
2025 ▪ Q2

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).]

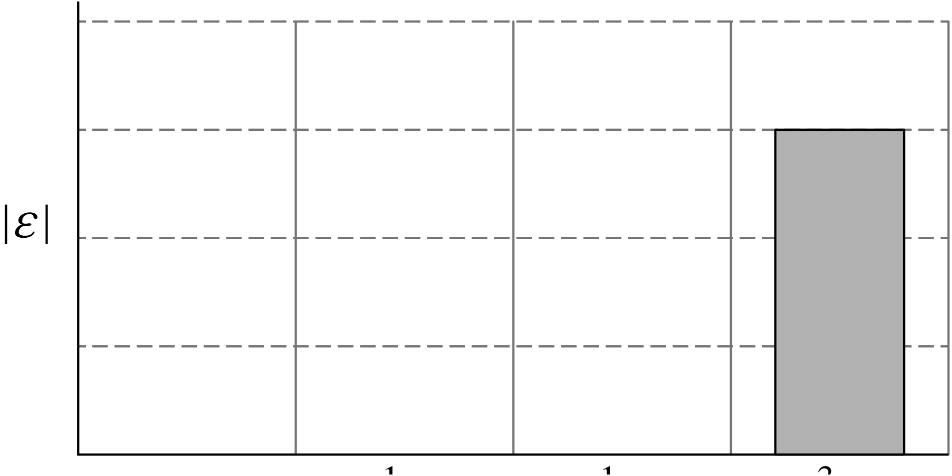
Question 2

(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.]

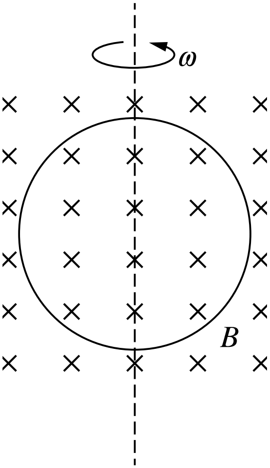
Question 2



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*toT*, (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

2024 Set 1 ▪ Q3

[Figure 1: An x-z coordinate system indicator (with $+z$ up, $+x$ to the right) is shown at top right. A rigid rectangular loop of width L and height $2L$ lies in the plane of the page, with corners forming a rectangle; the loop's leading (right) vertical edge is labeled with an arrow pointing right labeled v, indicating the loop moves in the $+x$-direction with constant speed v. Inside the loop near its left edge, a resistor R (zigzag symbol) is shown in the left vertical side, and point S is marked at the midpoint of the loop's right (leading) edge. To the right of the loop, the page is divided into two vertical field regions along the x-axis: "Region 1" spans from $x = L$ to $x = 2L$, shown with dots (indicating field out of the page, $+z$-direction); "Region 2" spans from $x = 2.5L$ to $x = 3.5L$, shown with alternating dot/cross symbols (two external uniform magnetic fields of equal magnitude B directed in opposite z-directions). The horizontal axis below is marked with tick labels $0, L, 2L, 3L, 4L$.]

Question 3

A wire is connected to a resistor of resistance R to form a rigid rectangular loop of width L and height $2L$. An external force is exerted on the loop so that the loop always moves with constant speed v in the $+x$-direction, as shown in Figure 1. The loop first enters Region 1 of external uniform magnetic field of magnitude B that is directed in the $-z$-direction. Region 1 has boundaries $x = L$ and $x = 2L$. The loop later enters Region 2 with two external, uniform magnetic fields, each of magnitude B, but directed in opposite z-directions. Region 2 has boundaries $x = 2.5L$ and $x = 3.5L$. Point S is the midpoint of the loop's leading edge B that is directed at the horizontal boundary in Region 2 that separates the two magnetic fields.

(a) [Figure: A blank graph with vertical axis Φ (unlabeled scale) and horizontal axis x marked with gridlines and tick labels $0, L, 2L, 3L, 4L, 4.5L$ (position of Point S from $x = 0$ to $x = 4.5L$).]

Question 3

On the following axes, **sketch** a graph of the magnetic flux Φ through the rectangular loop as a function of the position x of Point S from $x = 0$ to $x = 4.5L$. The $+z$-direction indicated in Figure 1 corresponds to $+\Phi$.

Question 3

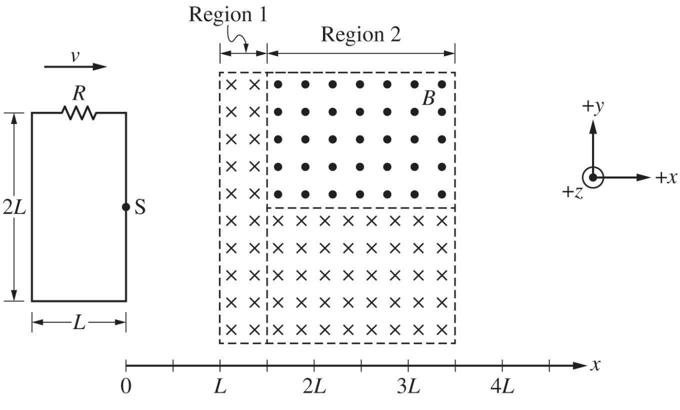


Figure 2

Question 3

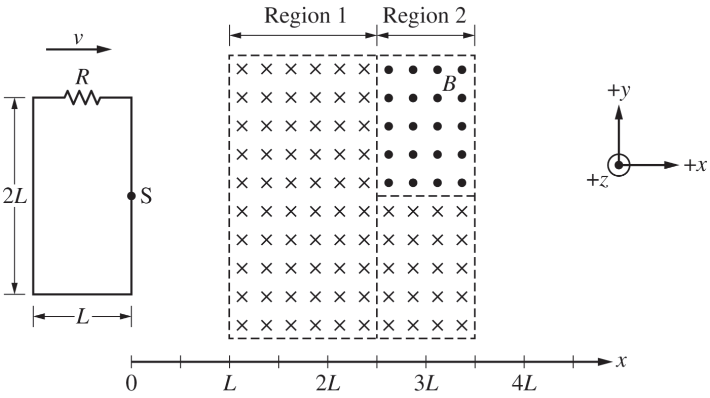
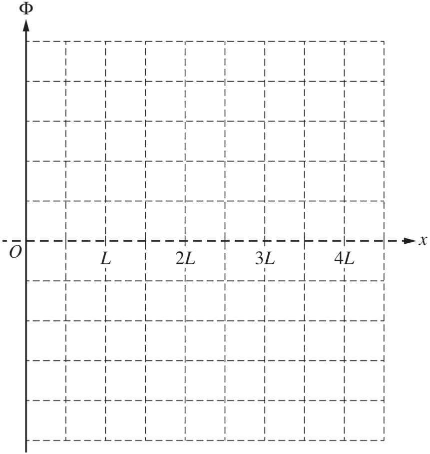


Figure 1

Question 3



Question 3

2024 Set 1 ▪ Q3

[Figure 1: An x-z coordinate system indicator (with $+z$ up, $+x$ to the right) is shown at top right. A rigid rectangular loop of width L and height $2L$ lies in the plane of the page, with corners forming a rectangle; the loop's leading (right) vertical edge is labeled with an arrow pointing right labeled v, indicating the loop moves in the $+x$-direction with constant speed v. Inside the loop near its left edge, a resistor R (zigzag symbol) is shown in the left vertical side, and point S is marked at the midpoint of the loop's right (leading) edge. To the right of the loop, the page is divided into two vertical field regions along the x-axis: "Region 1" spans from $x = L$ to $x = 2L$, shown with dots (indicating field out of the page, $+z$-direction); "Region 2" spans from $x = 2.5L$ to $x = 3.5L$, shown with alternating dot/cross symbols (two external uniform magnetic fields of equal magnitude B directed in opposite z-directions). The horizontal axis below is marked with tick labels $0, L, 2L, 3L, 4L$.]

A wire is connected to a resistor of resistance R to form a rigid rectangular loop of width L and height $2L$. An external force is exerted on the loop so that the loop always moves with

Question 3

constant speed v in the $+x$-direction, as shown in Figure 1. The loop first enters Region 1 of external uniform magnetic field of magnitude B that is directed in the $-z$-direction. Region 1 has boundaries $x = L$ and $x = 2L$. The loop later enters Region 2 with two external, uniform magnetic fields, each of magnitude B, but directed in opposite z-directions. Region 2 has boundaries $x = 2.5L$ and $x = 3.5L$. Point S is the midpoint of the loop's leading edge B that is directed at the horizontal boundary in Region 2 that separates the two magnetic fields.

(b)(i) Consider the instant when Point S reaches $x = 1.5L$.

Indicate whether the current I_R that is induced in the rectangular loop when Point S reaches $x = 1.5L$ is clockwise, counterclockwise, or zero.

______ Clockwise ______ Counterclockwise ______ Zero

Briefly **justify** your answer.

Question 3

(b)(ii) Derive an expression for I_R when Point S reaches $x = 1.5L$. If $I_R = 0$, indicate how the derived expression shows that $I_R = 0$. Express your answer in terms of R, L, v, B, and physical constants, as appropriate.

(b)(iii) Derive an expression for the power P dissipated by the resistor when Point S reaches $x = 1.5L$. Express your answer in terms of R, L, v, B, and physical constants, as appropriate.

Question 3

2024 Set 1 ▪ Q3

[Figure 1: An x-z coordinate system indicator (with $+z$ up, $+x$ to the right) is shown at top right. A rigid rectangular loop of width L and height $2L$ lies in the plane of the page, with corners forming a rectangle; the loop's leading (right) vertical edge is labeled with an arrow pointing right labeled v, indicating the loop moves in the $+x$-direction with constant speed v. Inside the loop near its left edge, a resistor R (zigzag symbol) is shown in the left vertical side, and point S is marked at the midpoint of the loop's right (leading) edge. To the right of the loop, the page is divided into two vertical field regions along the x-axis: "Region 1" spans from $x = L$ to $x = 2L$, shown with dots (indicating field out of the page, $+z$-direction); "Region 2" spans from $x = 2.5L$ to $x = 3.5L$, shown with alternating dot/cross symbols (two external uniform magnetic fields of equal magnitude B directed in opposite z-directions). The horizontal axis below is marked with tick labels $0, L, 2L, 3L, 4L$.]

A wire is connected to a resistor of resistance R to form a rigid rectangular loop of width L and height $2L$. An external force is exerted on the loop so that the loop always moves with

Question 3

constant speed v in the $+x$-direction, as shown in Figure 1. The loop first enters Region 1 of external uniform magnetic field of magnitude B that is directed in the $-z$-direction. Region 1 has boundaries $x = L$ and $x = 2L$. The loop later enters Region 2 with two external, uniform magnetic fields, each of magnitude B, but directed in opposite z-directions. Region 2 has boundaries $x = 2.5L$ and $x = 3.5L$. Point S is the midpoint of the loop's leading edge B that is directed at the horizontal boundary in Region 2 that separates the two magnetic fields.

(c) The total energy dissipated by the resistor in the rectangular loop as Point S moves from $x = 0$ to $x = 4.5L$ is E_{original}.

The vertical boundary between regions 1 and 2 is now shifted to $x = 1.5L$. After the boundary is shifted, the rectangular loop again moves with speed v in the $+x$-direction, as shown in Figure 2. The total energy dissipated by the resistor as Point S moves from $x = 0$ to $x = 4.5L$ is E_{new}.

Question 3

[Figure 2: Same setup as Figure 1, but Region 1 (dots, $+z$ field out of page) now spans from $x = L$ to $x = 1.5L$, and Region 2 (alternating dot/cross field) spans from $x = 1.5L$ to $x = 2.5L$. The loop, resistor R, and point S are shown in the same configuration as before, moving in $+x$ with speed v. Axis tick labels: $0, L, 2L, 3L, 4L$.]
Indicate whether E_{new} is greater than, less than, or equal to E_{original}.
______$E_{\text{new}} > E_{\text{original}}$ ______$E_{\text{new}} < E_{\text{original}}$ ______$E_{\text{new}} = E_{\text{original}}$
Briefly **justify** your answer.

Question 3

2024 Set 1 ▪ Q3

[Figure 1: An x-z coordinate system indicator (with $+z$ up, $+x$ to the right) is shown at top right. A rigid rectangular loop of width L and height $2L$ lies in the plane of the page, with corners forming a rectangle; the loop's leading (right) vertical edge is labeled with an arrow pointing right labeled v, indicating the loop moves in the $+x$-direction with constant speed v. Inside the loop near its left edge, a resistor R (zigzag symbol) is shown in the left vertical side, and point S is marked at the midpoint of the loop's right (leading) edge. To the right of the loop, the page is divided into two vertical field regions along the x-axis: "Region 1" spans from $x = L$ to $x = 2L$, shown with dots (indicating field out of the page, $+z$-direction); "Region 2" spans from $x = 2.5L$ to $x = 3.5L$, shown with alternating dot/cross symbols (two external uniform magnetic fields of equal magnitude B directed in opposite z-directions). The horizontal axis below is marked with tick labels $0, L, 2L, 3L, 4L$.]

A wire is connected to a resistor of resistance R to form a rigid rectangular loop of width L and height $2L$. An external force is exerted on the loop so that the loop always moves with

Question 3

constant speed v in the $+x$-direction, as shown in Figure 1. The loop first enters Region 1 of external uniform magnetic field of magnitude B that is directed in the $-z$-direction. Region 1 has boundaries $x = L$ and $x = 2L$. The loop later enters Region 2 with two external, uniform magnetic fields, each of magnitude B, but directed in opposite z-directions. Region 2 has boundaries $x = 2.5L$ and $x = 3.5L$. Point S is the midpoint of the loop's leading edge B that is directed at the horizontal boundary in Region 2 that separates the two magnetic fields.

(d) [Figure 3: A right-triangular loop with base L and height $2L$ is shown, with a resistor R on its vertical left side and point S at the lower-right corner (lower leading corner) of the loop. To the right, the region $L < x < 3.5L$ contains a uniform magnetic field of magnitude B shown with cross symbols (directed in the $-z$-direction). The loop moves in the $+x$-direction with speed v. Axis tick labels: $0, L, 2L, 3L, 4L$.]

The original magnetic fields are modified so that the region $L < x < 3.5L$ contains an external uniform magnetic field of magnitude B that is directed in the $-z$-direction.

Question 3

A new wire is connected to a resistor of resistance R to form a rigid triangular loop with base length L and height $2L$. An external force is exerted on the loop so that the loop always moves with speed v in the $+x$-direction, as shown in Figure 3. Point S represents the lower-leading corner of the loop.
[Figure: A blank graph with vertical axis I_S (unlabeled scale) and horizontal axis x marked with gridlines and tick labels $0, L, 2L, 3L, 4L$.]
On the following axes, **sketch** a graph of the induced current I_S in the triangular loop as Point S moves from $x = L$ to $x = 3L$.

Solution 3

(a) Mark scheme

- Sketch magnetic flux Φ through the rectangular loop versus position x of Point S, from $x = 0$ to $x = 4.5L$, 4 points total (1 pt each region): (1) flux is zero for $0 \leq x \leq L$ and for $x > 3.5L$; (2) the absolute value of the flux increases with a constant slope for $L < x < 2L$; (3) the flux is constant and nonzero for $2L < x < 2.5L$; (4) the absolute value of the flux decreases from its nonzero value at $x = 2.5L$ to zero at $x = 3.5L$. (A sketch reflected across the horizontal axis also earns full credit; the magnitudes of the slopes in the ramp regions are not scored.) Shape: flat at zero from 0 to L, ramps to a (negative, since $+z$ is $+\Phi$ and the field here is into the page) plateau between roughly 2L-2.5L, ramps back to zero by 3.5L, flat afterward to 4.5L.

Solution 3

(b)(i)

Mark scheme

- Select Counterclockwise, with an attempt at justification (1 pt). The justification must indicate either that the magnetic flux through the loop is increasing in the $-z$-direction, OR that the magnetic field due to the induced current will be directed in the $+z$-direction (1 pt). Reasoning: by Lenz's law the induced current opposes the increasing $-z$ flux by creating a field in $+z$ inside the loop, which (by the right-hand rule) requires a counterclockwise current.

Solution 3

(b)(ii) Mark scheme

- Derive I_R using Faraday's law, 3 points: (1) a multistep derivation that includes Faraday's law, $\mathcal{E} = -\frac{d\Phi_B}{dt} = -\frac{d}{dt}(BA)$ (1 pt; the point is earned even if the negative sign is omitted); (2) indicate that $\frac{dA}{dt} = 2Lv$ (1 pt; sign not required) since the loop's covered area within the field grows at rate $2L \cdot v$ as Point S advances; (3) apply Ohm's law to obtain an expression for I_R consistent with the derived emf (1 pt; sign not required). Result: $\mathcal{E} = B\frac{dA}{dt} = 2BLv$, so $I_R = \frac{2BLv}{R}$.

Solution 3

(b)(iii) Mark scheme

- Derive the dissipated power P: (1) use a correct general expression for power, $P = I^2R$ or $P = \frac{(\Delta V)^2}{R}$ or $P = I\Delta V$ (1 pt); (2) substitute the I_R expression from part (b)(ii) to write P in terms of the given quantities R, L, v, B only, consistently with that earlier response (1 pt). Result: $P = \frac{(2BLv)^2}{R} = \frac{4B^2L^2v^2}{R}$.

Solution 3

(c) Mark scheme

- Select $E_{\text{new}} < E_{\text{original}}$, with an attempt at a relevant justification (1 pt). The justification must indicate one of: the change in magnetic flux is greater for the original scenario, the induced current occurs for a greater amount of time in the original scenario, or the induced emf occurs for a greater amount of time in the original scenario (1 pt). Reasoning: shifting the field-region boundary to $x = 1.5L$ reduces the flux change and/or the duration over which emf/current is induced compared to the original setup, so less total energy is dissipated in the resistor: $E_{\text{new}} < E_{\text{original}}$.

Solution 3

(d)

Mark scheme

- Sketch the magnitude of the induced current I_T versus x for the triangular-loop scenario with the field region now $L < x < 3.5L$: (1) the sketch's absolute value only increases (e.g., roughly linearly, reflecting the growing chord length of the triangle) from $x = L$ to $x = 2L$ (1 pt); (2) the sketch is zero from $x = 2L$ to $x = 3L$ (the loop is fully inside the field region with constant flux) (1 pt). (A response reflected across the horizontal axis earns both points; any portion of the graph before $x = L$ or after $x = 3L$ is not scored.)

Question 2

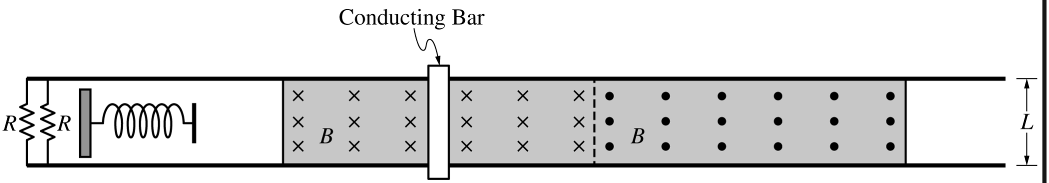
2023 Set 1 ▪ Q2

Two horizontal, parallel, conducting rails are separated by distance $L = 0.40\,\text{m}$. A resistor of resistance $R = 0.30\,\Omega$ connects the rails. A horizontal ideal spring is located between the rails. The right end of the spring is free to move and the left end is fixed in place. A conducting bar of mass $m = 0.23\,\text{kg}$ is placed on the rails and is in contact with the spring, which is initially compressed. Frictional forces and the resistance of the bar and rails are negligible.
- At time $t = 0$, the bar is released from rest and is pushed to the right by the spring. - At time t_1, the bar loses contact with the spring and slides to the right. - At time t_2, the bar enters and travels through a uniform magnetic field of magnitude $B = 0.50\,\text{T}$ that is directed into the page, as shown. - At time t_3, the bar enters a region where the magnitude of the uniform magnetic field is still $B = 0.50\,\text{T}$ but is directed out of the page. - At time t_4, the bar enters a region with no magnetic field.

Question 2

Consider time t_B such that $t_2 < t_B < t_3$.
[Diagram: Top view at time t_B. Two horizontal parallel rails separated by distance L, connected on the left by a resistor R and a coiled spring, with the Conducting Bar shown between two field regions. The left field region (between the spring/bar and the bar's current position) is shaded with $\times$ symbols labeled B, indicating a uniform magnetic field into the page. The right region is marked with $\cdot$ (dot) symbols labeled B, indicating a uniform magnetic field out of the page.]
(a) On the following diagram of the bar, draw an arrow indicating the direction of the net force F_{net} exerted on the bar at time t_B. If the net force is zero, write $F_{net} = 0$.
[Diagram: A vertical rectangle representing the conducting bar, for the student to draw a force arrow on.]

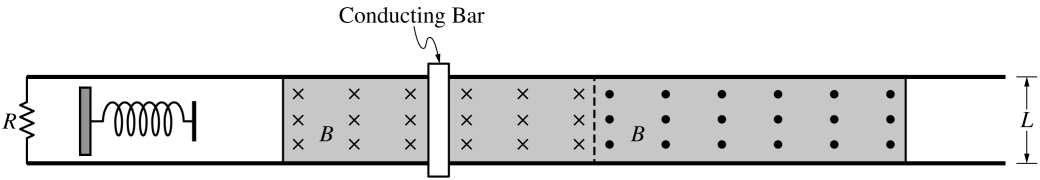
Question 2



Top View (at time t_B)

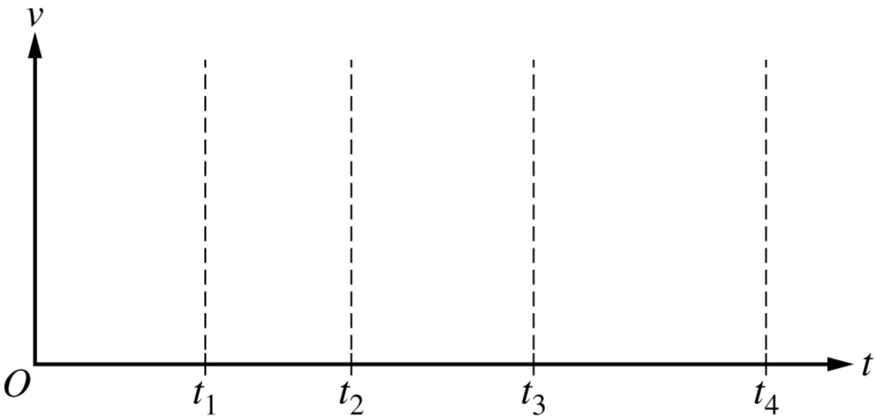
) The scenario is repeated but an additional resistor of resistance $R = 0.20\ \Omega$ is connected, as shown

Question 2



Top View (at time t_B)

Question 2



Question 2

2023 Set 1 ▪ Q2

Two horizontal, parallel, conducting rails are separated by distance $L = 0.40\,\text{m}$. A resistor of resistance $R = 0.30\,\Omega$ connects the rails. A horizontal ideal spring is located between the rails. The right end of the spring is free to move and the left end is fixed in place. A conducting bar of mass $m = 0.23\,\text{kg}$ is placed on the rails and is in contact with the spring, which is initially compressed. Frictional forces and the resistance of the bar and rails are negligible.
- At time $t = 0$, the bar is released from rest and is pushed to the right by the spring. - At time t_1, the bar loses contact with the spring and slides to the right. - At time t_2, the bar enters and travels through a uniform magnetic field of magnitude $B = 0.50\,\text{T}$ that is directed into the page, as shown. - At time t_3, the bar enters a region where the magnitude of the uniform magnetic field is still $B = 0.50\,\text{T}$ but is directed out of the page. - At time t_4, the bar enters a region with no magnetic field.
Consider time t_B such that $t_2 < t_B < t_3$.

Question 2

[Diagram: Top view at time t_B. Two horizontal parallel rails separated by distance L, connected on the left by a resistor R and a coiled spring, with the Conducting Bar shown between two field regions. The left field region (between the spring/bar and the bar's current position) is shaded with $\times$ symbols labeled B, indicating a uniform magnetic field into the page. The right region is marked with $\cdot$ (dot) symbols labeled B, indicating a uniform magnetic field out of the page.]

(b)(i) At time t_B, the speed of the bar is $v = 2.5\,\mathrm{m/s}$.

Calculate the magnitude of the current in the bar at time t_B.

(b)(ii) Calculate the magnitude of the net force F_{net} exerted on the bar at time t_B.

Question 2

2023 Set 1 ▪ Q2

Two horizontal, parallel, conducting rails are separated by distance $L = 0.40\,\mathrm{m}$. A resistor of resistance $R = 0.30\,\Omega$ connects the rails. A horizontal ideal spring is located between the rails. The right end of the spring is free to move and the left end is fixed in place. A conducting bar of mass $m = 0.23\,\mathrm{kg}$ is placed on the rails and is in contact with the spring, which is initially compressed. Frictional forces and the resistance of the bar and rails are negligible.
- At time $t = 0$, the bar is released from rest and is pushed to the right by the spring. - At time t_1, the bar loses contact with the spring and slides to the right. - At time t_2, the bar enters and travels through a uniform magnetic field of magnitude $B = 0.50\,\mathrm{T}$ that is directed into the page, as shown. - At time t_3, the bar enters a region where the magnitude of the uniform magnetic field is still $B = 0.50\,\mathrm{T}$ but is directed out of the page. - At time t_4, the bar enters a region with no magnetic field.
Consider time t_B such that $t_2 < t_B < t_3$.

Question 2

[Diagram: Top view at time t_B. Two horizontal parallel rails separated by distance L, connected on the left by a resistor R and a coiled spring, with the Conducting Bar shown between two field regions. The left field region (between the spring/bar and the bar's current position) is shaded with $\times$ symbols labeled B, indicating a uniform magnetic field into the page. The right region is marked with $\cdot$ (dot) symbols labeled B, indicating a uniform magnetic field out of the page.]

(c) On the following axes, sketch a graph of the speed v of the bar as a function of time t between $t = 0$ and t_4.

[Graph: Blank axes with vertical axis v and horizontal axis t, origin labeled O. Four vertical dashed reference lines are marked on the horizontal axis at t_1, t_2, t_3, and t_4, for the student to sketch the speed-time curve.]

Question 2

2023 Set 1 ▪ Q2

Two horizontal, parallel, conducting rails are separated by distance $L = 0.40\,\mathrm{m}$. A resistor of resistance $R = 0.30\,\Omega$ connects the rails. A horizontal ideal spring is located between the rails. The right end of the spring is free to move and the left end is fixed in place. A conducting bar of mass $m = 0.23\,\mathrm{kg}$ is placed on the rails and is in contact with the spring, which is initially compressed. Frictional forces and the resistance of the bar and rails are negligible.
- At time $t = 0$, the bar is released from rest and is pushed to the right by the spring. - At time t_1, the bar loses contact with the spring and slides to the right. - At time t_2, the bar enters and travels through a uniform magnetic field of magnitude $B = 0.50\,\mathrm{T}$ that is directed into the page, as shown. - At time t_3, the bar enters a region where the magnitude of the uniform magnetic field is still $B = 0.50\,\mathrm{T}$ but is directed out of the page. - At time t_4, the bar enters a region with no magnetic field.
Consider time t_B such that $t_2 < t_B < t_3$.

Question 2

[Diagram: Top view at time t_B. Two horizontal parallel rails separated by distance L, connected on the left by a resistor R and a coiled spring, with the Conducting Bar shown between two field regions. The left field region (between the spring/bar and the bar's current position) is shaded with $\times$ symbols labeled B, indicating a uniform magnetic field into the page. The right region is marked with $\cdot$ (dot) symbols labeled B, indicating a uniform magnetic field out of the page.]

(d)(i) The scenario is repeated but an additional resistor of resistance $R = 0.30\,\Omega$ is connected, as shown.

[Diagram: Top view at time t_B, same rail/bar/field setup as before, but now with a second resistor R connected in the circuit next to the first resistor R and the spring, both on the left end of the rails.]

Determine the total resistance R_{total} of the closed circuit for the new scenario.

(d)(ii) In the original scenario, the magnitude of the acceleration of the bar immediately after the bar enters the first uniform magnetic field is $a_{original}$. In the new

Question 2

scenario, the magnitude of the acceleration of the bar immediately after the bar enters the first uniform magnetic field is a_{new}.
Is a_{new} greater than, less than, or equal to $a_{original}$? Justify your answer.

Question 2

2023 Set 1 ▪ Q2

Two horizontal, parallel, conducting rails are separated by distance $L = 0.40\,\mathrm{m}$. A resistor of resistance $R = 0.30\,\Omega$ connects the rails. A horizontal ideal spring is located between the rails. The right end of the spring is free to move and the left end is fixed in place. A conducting bar of mass $m = 0.23\,\mathrm{kg}$ is placed on the rails and is in contact with the spring, which is initially compressed. Frictional forces and the resistance of the bar and rails are negligible.
- At time $t = 0$, the bar is released from rest and is pushed to the right by the spring. - At time t_1, the bar loses contact with the spring and slides to the right. - At time t_2, the bar enters and travels through a uniform magnetic field of magnitude $B = 0.50\,\mathrm{T}$ that is directed into the page, as shown. - At time t_3, the bar enters a region where the magnitude of the uniform magnetic field is still $B = 0.50\,\mathrm{T}$ but is directed out of the page. - At time t_4, the bar enters a region with no magnetic field.
Consider time t_B such that $t_2 < t_B < t_3$.

Question 2

[Diagram: Top view at time t_B. Two horizontal parallel rails separated by distance L, connected on the left by a resistor R and a coiled spring, with the Conducting Bar shown between two field regions. The left field region (between the spring/bar and the bar's current position) is shaded with $\times$ symbols labeled B, indicating a uniform magnetic field into the page. The right region is marked with $\cdot$ (dot) symbols labeled B, indicating a uniform magnetic field out of the page.]

(e) Describe a modification to m, B, or L that will result in a smaller induced potential difference across the original resistor immediately after the bar enters the first uniform magnetic field. Justify your answer.

Solution 2

(a)

Mark scheme

- At time t_B the induced current in the bar produces a magnetic (retarding) force that, by Lenz's law, opposes the bar's motion into the field; draw a single arrow on the bar pointing to the left, with no other/extraneous force arrows included. (If a student instead correctly argues the net force is zero at t_B, write $F_{net} = 0$ for full credit.) 1 point total for a correct single left-pointing arrow with no extraneous arrows.

Solution 2

(b)(i) Mark scheme

- Faraday's law: $\mathcal{E} = -\dfrac{d\Phi_B}{dt} = -\dfrac{d(BLx)}{dt}$ (1 pt, using Faraday's law to set up the induced emf; may be earned without the negative sign or a numerical answer). Substituting $v = \dfrac{dx}{dt}$: $\mathcal{E} = -BL\dfrac{dx}{dt} = -BLv$ (1 pt, correct substitution of v for dx/dt; points 1 and 2 may also be earned by starting directly from $\mathcal{E} = BLv$). Numerically, $\mathcal{E} = -(0.50\,\mathrm{T})(0.40\,\mathrm{m})(2.5\,\mathrm{m/s}) = -0.50\,\mathrm{V}$. Using Ohm's law with the correct resistance (1 pt, substituting the correct resistance into Ohm's law to solve for current): $I = \dfrac{|\mathcal{E}|}{R} = \dfrac{|-0.50\,\mathrm{V}|}{0.30\,\Omega} = 1.7\,\mathrm{A}$.

Solution 2

(b)(ii) Mark scheme

- Substituting the current from part (b)(i) into the magnetic force equation: $\vec{F} = \int I\, d\vec{\ell} \times \vec{B} \Rightarrow F = ILB = (1.7\,\mathrm{A})(0.4\,\mathrm{m})(0.5\,\mathrm{T}) = 0.33\,\mathrm{N}$ (equivalently, using $F = \frac{B^2L^2v}{R} = \frac{(0.5)^2(0.4)^2(2.5)}{0.3} = 0.33\,\mathrm{N}$). 1 point for substituting the current (or an expression for it) into an appropriate equation for the magnetic force on the bar and obtaining $F = 0.33\,\mathrm{N}$.

Solution 2

(c)

Mark scheme

- Sketch of speed v vs. time t from $t = 0$ to t_4: the curve starts at the origin, is increasing and concave down from $t = 0$ to t_1 (1 pt); is a horizontal line (constant speed) from t_1 to t_2 (1 pt); is decreasing and concave up from t_2 to t_4 (1 pt); and is differentiable (smooth, no sharp corner) at t_3 with a nonzero slope there (1 pt) — i.e. the curve rises smoothly to a plateau between t_1 and t_2, then decays smoothly and without a kink through t_3 on its way down to t_4.

Solution 2

(d)(i) Mark scheme

- The two $0.30\,\Omega$ resistors are now in parallel: $\dfrac{1}{R_p} = \dfrac{1}{0.3\,\Omega} + \dfrac{1}{0.3\,\Omega} = \dfrac{2}{0.3\,\Omega} \Rightarrow R_p = 0.15\,\Omega$. 1 point for the correct numeric answer with units $(0.15\,\Omega)$; this point can be earned without supporting calculations shown.

Solution 2

(d)(ii) Mark scheme

- a_{new} is greater than $a_{original}$. Chain of reasoning (each statement worth 1 point, full credit earnable with a justification consistent with the resistance calculated in part (d)(i)): since the new total resistance is smaller ($0.15\,\Omega < 0.30\,\Omega$), the current increases (inverse relationship between resistance and current) (1 pt); since the current increases, the magnetic force on the bar increases (direct relationship between current and force, via $F = BIL$) (1 pt); since the force increases, the magnitude of the bar's acceleration increases (direct relationship between force and acceleration, via $F = ma$) (1 pt). Example: "Since there is less resistance in the new circuit, there will be more current in the new circuit, so a

Solution 2

larger force on the bar. Thus, since the force on the bar is larger, the new acceleration is greater than the original acceleration."

Solution 2

(e) Mark scheme

- Any ONE of the following modifications, with an attempt at justification (1 pt): decreasing B, decreasing L, or increasing m. A second point (1 pt) is earned for correctly justifying why the chosen modification results in a smaller induced potential difference across the original resistor. Since $\mathcal{E} = -BLv$: decreasing B directly decreases $\mathcal{E}$ (proportional relationship); decreasing L directly decreases $\mathcal{E}$ (proportional relationship, L is the rail separation); increasing m causes the bar to enter the field with a smaller speed v (e.g., if launched by the same spring/energy source, larger mass gives smaller speed), and since $\mathcal{E} \propto v$, a smaller v gives a smaller induced $\mathcal{E}$.

Question 2

2023 Set 2 ▪ Q2

[Figure, Perspective View (at time $t = 0$): A sloped section of two parallel conducting rails at height H, with a resistor R at the top of the slope. The rails transition to a horizontal section. A region of magnetic field B_1 (dots, pointing out of the page, +y-direction) covers part of the horizontal rails near the bottom of the slope. Farther along, a separate region of magnetic field B_2 (arrows pointing into the page, +z-direction, shown as downward-slanting field lines with arrowheads) covers another part of the rails. Axes shown: $+x$, $+y$, $+z$ in a right-handed orientation.]
[Figure, Top View (at time t_B): Two horizontal parallel rails separated by distance d, viewed from above. A resistor R is at the left end (position x_0). The bar is shown as a vertical rectangle. Positions marked along the x-axis: x_0, x_1, x_B, x_2, x_3, x_4. The region between x_1 and x_2 is shaded with dots labeled B_1 (field out of the page). The region

Question 2

between x_3 and x_4 has downward arrows labeled B_2 (field into the page). The bar is shown at position x_B, between x_1 and x_2.]
Two parallel conducting rails are separated by distance $d = 0.30$ m. A resistor of resistance $R = 0.20\ \Omega$ connects the rails. A conducting bar is placed on a sloped section of the rails at height H above the horizontal section of the rails. Frictional forces and the resistances of the bar and rails are negligible.
- At time $t = 0$, the bar is released from rest from position x_0 and slides down the sloped section of the rails, as shown in the Perspective View. - At time t_1, the bar reaches position x_1 and smoothly transitions to the horizontal section of the rails and enters a uniform magnetic field of magnitude $B_1 = 0.40$ T that is directed in the $+$y-direction. - At time t_2, the bar reaches position x_2 and enters a region with no magnetic field. - At time t_3, the bar reaches position x_3 and enters a uniform magnetic

Question 2

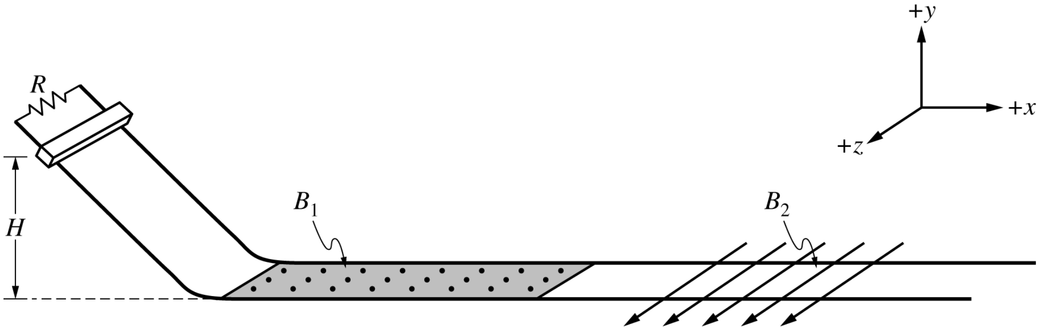
field of magnitude $B_2 = 0.60$ T that is directed in the +z-direction. - At time t_4, the bar reaches position x_4 and enters a region with no magnetic field.

The bar is at position x_B (shown in Top View) at time t_B such that $t_1 < t_B < t_2$.

(a) [Diagram: a vertical rectangle representing the bar, viewed from the Top View perspective, with no arrows drawn.]

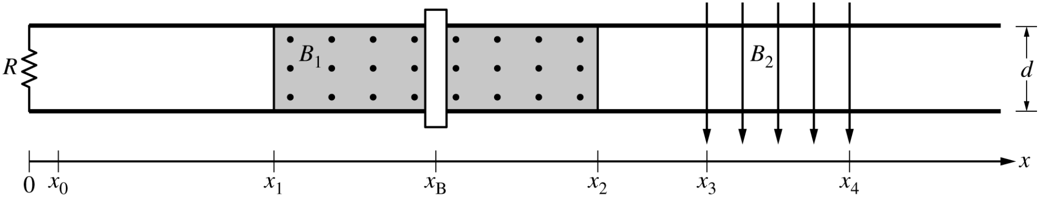
On the following diagram of the bar, as observed from the Top View, draw an arrow indicating the direction of the net force F_{net} exerted on the bar at time t_B. If the net force is zero, write $F_{\text{net}} = 0$.

Question 2



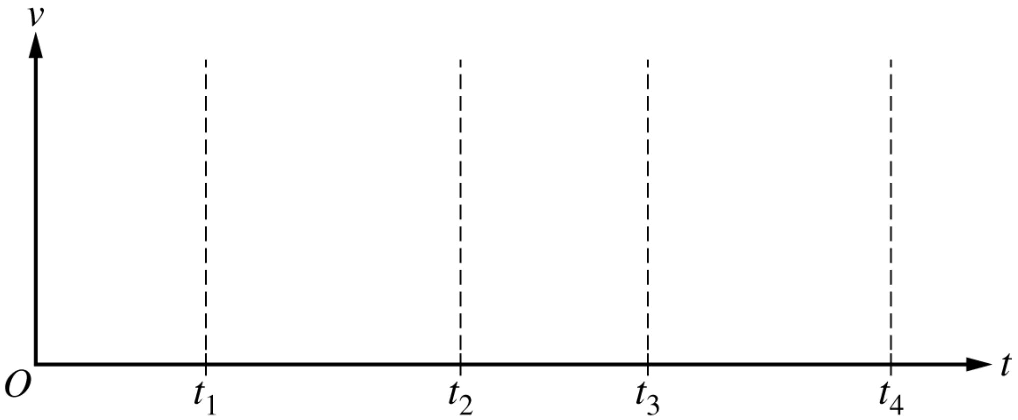
Perspective View (at time $t = 0$)

Question 2



Top View (at time t_B)

Question 2



Question 2

2023 Set 2 ▪ Q2

[Figure, Perspective View (at time $t = 0$): A sloped section of two parallel conducting rails at height H, with a resistor R at the top of the slope. The rails transition to a horizontal section. A region of magnetic field B_1 (dots, pointing out of the page, +y-direction) covers part of the horizontal rails near the bottom of the slope. Farther along, a separate region of magnetic field B_2 (arrows pointing into the page, +z-direction, shown as downward-slanting field lines with arrowheads) covers another part of the rails. Axes shown: $+x$, $+y$, $+z$ in a right-handed orientation.]

[Figure, Top View (at time t_B): Two horizontal parallel rails separated by distance d, viewed from above. A resistor R is at the left end (position x_0). The bar is shown as a vertical rectangle. Positions marked along the x-axis: x_0, x_1, x_B, x_2, x_3, x_4. The region between x_1 and x_2 is shaded with dots labeled B_1 (field out of the page). The region between x_3 and x_4 has downward arrows labeled B_2 (field into the page). The bar is shown at position x_B, between x_1 and x_2.]

Question 2

Two parallel conducting rails are separated by distance $d = 0.30$ m. A resistor of resistance $R = 0.20\ \Omega$ connects the rails. A conducting bar is placed on a sloped section of the rails at height H above the horizontal section of the rails. Frictional forces and the resistances of the bar and rails are negligible.
- At time $t = 0$, the bar is released from rest from position x_0 and slides down the sloped section of the rails, as shown in the Perspective View. - At time t_1, the bar reaches position x_1 and smoothly transitions to the horizontal section of the rails and enters a uniform magnetic field of magnitude $B_1 = 0.40$ T that is directed in the $+$y-direction. - At time t_2, the bar reaches position x_2 and enters a region with no magnetic field. - At time t_3, the bar reaches position x_3 and enters a uniform magnetic field of magnitude $B_2 = 0.60$ T that is directed in the $+$z-direction. - At time t_4, the bar reaches position x_4 and enters a region with no magnetic field.

The bar is at position x_B (shown in Top View) at time t_B such that $t_1 < t_B < t_2$.

(b)(i) At time t_B, the speed of the bar is $v = 2.5$ m/s.

Question 2

Calculate the magnitude of the current in the bar at time t_B.

(b)(ii) Calculate the magnitude of the net force F_{net} exerted on the bar at time t_B.

Question 2

2023 Set 2 ▪ Q2

[Figure, Perspective View (at time $t = 0$): A sloped section of two parallel conducting rails at height H, with a resistor R at the top of the slope. The rails transition to a horizontal section. A region of magnetic field B_1 (dots, pointing out of the page, +y-direction) covers part of the horizontal rails near the bottom of the slope. Farther along, a separate region of magnetic field B_2 (arrows pointing into the page, +z-direction, shown as downward-slanting field lines with arrowheads) covers another part of the rails. Axes shown: $+x$, $+y$, $+z$ in a right-handed orientation.]
[Figure, Top View (at time t_B): Two horizontal parallel rails separated by distance d, viewed from above. A resistor R is at the left end (position x_0). The bar is shown as a vertical rectangle. Positions marked along the x-axis: x_0, x_1, x_B, x_2, x_3, x_4. The region between x_1 and x_2 is shaded with dots labeled B_1 (field out of the page). The region between x_3 and x_4 has downward arrows labeled B_2 (field into the page). The bar is shown at position x_B, between x_1 and x_2.]

Question 2

Two parallel conducting rails are separated by distance $d = 0.30$ m. A resistor of resistance $R = 0.20\ \Omega$ connects the rails. A conducting bar is placed on a sloped section of the rails at height H above the horizontal section of the rails. Frictional forces and the resistances of the bar and rails are negligible.

- At time $t = 0$, the bar is released from rest from position x_0 and slides down the sloped section of the rails, as shown in the Perspective View. - At time t_1, the bar reaches position x_1 and smoothly transitions to the horizontal section of the rails and enters a uniform magnetic field of magnitude $B_1 = 0.40$ T that is directed in the $+$y-direction. - At time t_2, the bar reaches position x_2 and enters a region with no magnetic field. - At time t_3, the bar reaches position x_3 and enters a uniform magnetic field of magnitude $B_2 = 0.60$ T that is directed in the $+$z-direction. - At time t_4, the bar reaches position x_4 and enters a region with no magnetic field.

The bar is at position x_B (shown in Top View) at time t_B such that $t_1 < t_B < t_2$.

Question 2

(c) On the following axes, sketch a graph of the speed v of the bar as a function of time t between $t = 0$ and t_4.
[Graph: y-axis labeled "v", x-axis labeled "t" with tick marks at t_1, t_2, t_3, t_4 (dashed vertical gridlines at each); axes otherwise unlabeled with numeric values, origin at O.]

Question 2

2023 Set 2 ▪ Q2

[Figure, Perspective View (at time $t = 0$): A sloped section of two parallel conducting rails at height H, with a resistor R at the top of the slope. The rails transition to a horizontal section. A region of magnetic field B_1 (dots, pointing out of the page, +y-direction) covers part of the horizontal rails near the bottom of the slope. Farther along, a separate region of magnetic field B_2 (arrows pointing into the page, +z-direction, shown as downward-slanting field lines with arrowheads) covers another part of the rails. Axes shown: $+x$, $+y$, $+z$ in a right-handed orientation.]

[Figure, Top View (at time t_B): Two horizontal parallel rails separated by distance d, viewed from above. A resistor R is at the left end (position x_0). The bar is shown as a vertical rectangle. Positions marked along the x-axis: x_0, x_1, x_B, x_2, x_3, x_4. The region between x_1 and x_2 is shaded with dots labeled B_1 (field out of the page). The region between x_3 and x_4 has downward arrows labeled B_2 (field into the page). The bar is shown at position x_B, between x_1 and x_2.]

Question 2

Two parallel conducting rails are separated by distance $d = 0.30$ m. A resistor of resistance $R = 0.20\ \Omega$ connects the rails. A conducting bar is placed on a sloped section of the rails at height H above the horizontal section of the rails. Frictional forces and the resistances of the bar and rails are negligible.
- At time $t = 0$, the bar is released from rest from position x_0 and slides down the sloped section of the rails, as shown in the Perspective View. - At time t_1, the bar reaches position x_1 and smoothly transitions to the horizontal section of the rails and enters a uniform magnetic field of magnitude $B_1 = 0.40$ T that is directed in the $+$y-direction. - At time t_2, the bar reaches position x_2 and enters a region with no magnetic field. - At time t_3, the bar reaches position x_3 and enters a uniform magnetic field of magnitude $B_2 = 0.60$ T that is directed in the $+$z-direction. - At time t_4, the bar reaches position x_4 and enters a region with no magnetic field.
The bar is at position x_B (shown in Top View) at time t_B such that $t_1 < t_B < t_2$.

Question 2

(d)(i) The original scenario is repeated but with a new bar that has the same mass but with a nonnegligible resistance $R = 0.20\ \Omega$. The new bar is released from rest and smoothly transitions to the horizontal section of the rails and enters the first uniform magnetic field.
Determine the total resistance of the closed circuit.
(d)(ii) In the original scenario, the magnitude of the acceleration of the bar immediately after the bar enters the first uniform magnetic field is a_{original}. In the new scenario, the magnitude of the acceleration of the bar immediately after the bar enters the first uniform magnetic field is a_{new}. Is a_{new} greater than, less than, or equal to a_{original}? Justify your answer.

Question 2

2023 Set 2 ▪ Q2

[Figure, Perspective View (at time $t = 0$): A sloped section of two parallel conducting rails at height H, with a resistor R at the top of the slope. The rails transition to a horizontal section. A region of magnetic field B_1 (dots, pointing out of the page, +y-direction) covers part of the horizontal rails near the bottom of the slope. Farther along, a separate region of magnetic field B_2 (arrows pointing into the page, +z-direction, shown as downward-slanting field lines with arrowheads) covers another part of the rails. Axes shown: $+x$, $+y$, $+z$ in a right-handed orientation.]

[Figure, Top View (at time t_B): Two horizontal parallel rails separated by distance d, viewed from above. A resistor R is at the left end (position x_0). The bar is shown as a vertical rectangle. Positions marked along the x-axis: x_0, x_1, x_B, x_2, x_3, x_4. The region between x_1 and x_2 is shaded with dots labeled B_1 (field out of the page). The region between x_3 and x_4 has downward arrows labeled B_2 (field into the page). The bar is shown at position x_B, between x_1 and x_2.]

Question 2

Two parallel conducting rails are separated by distance $d = 0.30$ m. A resistor of resistance $R = 0.20\ \Omega$ connects the rails. A conducting bar is placed on a sloped section of the rails at height H above the horizontal section of the rails. Frictional forces and the resistances of the bar and rails are negligible.

- At time $t = 0$, the bar is released from rest from position x_0 and slides down the sloped section of the rails, as shown in the Perspective View. - At time t_1, the bar reaches position x_1 and smoothly transitions to the horizontal section of the rails and enters a uniform magnetic field of magnitude $B_1 = 0.40$ T that is directed in the $+$y-direction. - At time t_2, the bar reaches position x_2 and enters a region with no magnetic field. - At time t_3, the bar reaches position x_3 and enters a uniform magnetic field of magnitude $B_2 = 0.60$ T that is directed in the $+$z-direction. - At time t_4, the bar reaches position x_4 and enters a region with no magnetic field.

The bar is at position x_B (shown in Top View) at time t_B such that $t_1 < t_B < t_2$.

Question 2

(e) Describe a modification to H, B_1, or d that will result in a larger induced current in the new bar immediately after the bar enters the first magnetic field. Justify your answer.

Solution 2

(a)

Mark scheme

- On the Top View diagram of the bar, draw a single arrow pointing to the LEFT (with no extraneous arrows) representing the direction of the net force F_{net} on the bar at time t_B. This is the magnetic braking force from the induced current interacting with the field, which by Lenz's law opposes the bar's motion; on the horizontal rail section (no gravity component along the rails) it is the only horizontal force, so F_{net} points opposite the bar's velocity, i.e. to the left in the given view.

Solution 2

(b)(i) Mark scheme

- Calculate the magnitude of the current in the bar at t_B, where $v = 2.5$ m/s. (1) Use Faraday's law for the induced emf: $\mathcal{E} = -\frac{d\Phi_B}{dt} = -\frac{d(B_1 dx)}{dt}$ (this point may be earned without the negative sign or a numerical answer). (2) Substitute v for $\frac{dx}{dt}$: $\mathcal{E} = -B_1 d\frac{dx}{dt} = -B_1 dv$ (a student may also earn both of the first two points by starting directly from $\mathcal{E} = B_1 dv$). (3) Substitute the correct resistance into Ohm's law to solve for current. Full solution:
  $\mathcal{E} = -(0.40\,\mathrm{T})(0.30\,\mathrm{m})(2.5\,\mathrm{m/s}) = -0.30$ V; $I = \frac{|\mathcal{E}|}{R} = \frac{0.30\,\mathrm{V}}{0.20\,\Omega} = 1.5$ A.

Solution 2

(b)(ii)

Mark scheme

- Calculate the magnitude of the net force F_{net} on the bar at t_B by substituting the current (or an expression for it) from part (b)(i) into $F = IdB_1$: $F = (1.5\,\mathrm{A})(0.3\,\mathrm{m})(0.4\,\mathrm{T}) = 0.18$ N. (Equivalently, deriving symbolically: $F = \dfrac{B_1^2 d^2 v}{R} = \dfrac{(0.4)^2(0.3)^2(2.5)}{0.2} = 0.18$ N.)

Solution 2

(c) Mark scheme

- Sketch v vs t from $t = 0$ to t_4 with four required features (1 point each): (1) a straight line with POSITIVE slope starting at the origin from $t = 0$ to t_1 (bar speeding up before/while entering the field region); (2) a curve that is DECREASING and CONCAVE UP from t_1 to t_2 (bar decelerating due to the speed-dependent magnetic braking force, asymptotically slowing its rate of decrease); (3) a NONZERO horizontal line from t_2 to t_3 (constant nonzero speed); (4) a NONZERO horizontal line from t_3 to t_4 (constant nonzero speed continues, possibly at a different level than segment 3). Net shape: rises linearly, then curves down concave-up leveling off, then two flat nonzero segments.

Solution 2

(d)(i)

Mark scheme

- Determine the total resistance of the closed circuit for the new bar ($R = 0.20\ \Omega$) in series with the fixed rail/other resistance of $0.2\ \Omega$: $R_s = \sum_i R_i = (0.2\,\Omega) + (0.2\,\Omega) = 0.4\ \Omega.$ Correct answer with units (0.4 Ω) earns the point; it may be earned without supporting calculations.

Solution 2

(d)(ii) Mark scheme

- Determine whether a_{new} is greater than, less than, or equal to $a_{original}$, and justify: the correct answer is $a_{new} < a_{original}$. Full credit requires a chain of correct statements (1 point each, and full credit can be earned with a justification consistent with the resistance calculated in part (d)(i)): (1) inverse relation between resistance and current — as resistance increases, current decreases; (2) direct relation between current and magnetic force — as current decreases, magnetic force $F = IdB$ decreases; (3) direct relation between force and acceleration — by Newton's second law $F = ma$, as force decreases (same mass), acceleration decreases. Example justification: the new bar has greater total

Solution 2

resistance, so it carries less current, so the magnetic force on it is less, so (same mass) its acceleration is less than the original.

Solution 2

(e) Mark scheme

- Describe ONE modification to H, B_1, or d that results in a LARGER induced current in the new bar immediately after entering the first magnetic field, and justify it. (1 point) Correctly identify one of: increasing H, increasing B_1, or increasing d, with an attempted relevant justification. (1 point) Correctly justify why that change increases current. Any one of: Increasing H — a higher release height gives greater potential energy, hence greater kinetic energy/speed entering the field, giving a greater rate of change of flux, so by Faraday's law a greater emf and thus greater current. OR Increasing B_1 — a stronger field increases the flux through the circuit and its rate of change, giving a greater induced emf and thus greater current. OR Increasing d — a larger bar width increases the area enclosed

Solution 2

by the circuit, increasing flux and its rate of change, giving a greater induced emf and thus greater current.

Question 3

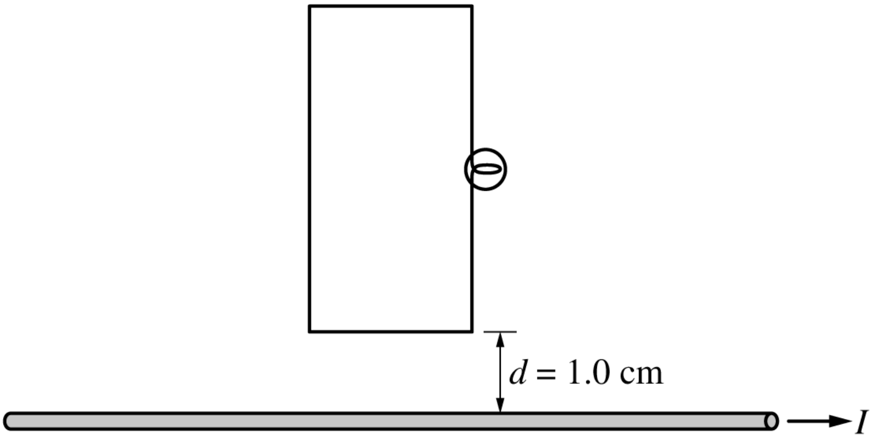
2022 Set 1 ▪ Q3

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.]

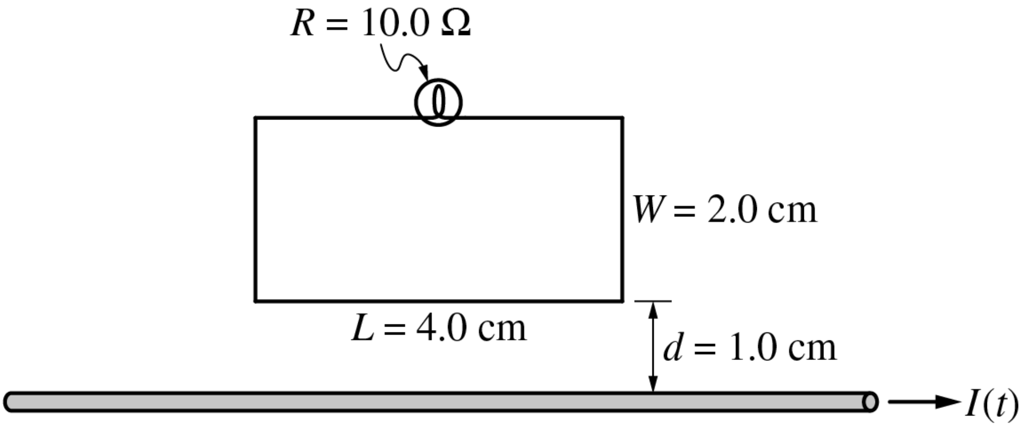
Question 3

(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

- $\varepsilon = \left|\dfrac{d\Phi}{dt}\right|$ (1 pt: using Faraday's law to determine the emf across the lightbulb). With $\Phi_B = \dfrac{\mu_0(C-Dt)L}{2\pi}\ln\left[\dfrac{d+W}{d}\right]$, differentiating (only $I(t) = C - Dt$ depends on t, with $dI/dt = -D$): $\varepsilon = \dfrac{\mu_0 DL}{2\pi}\ln\left[\dfrac{d+W}{d}\right]$. Then $I = \dfrac{\varepsilon}{R} = \dfrac{\mu_0 DL}{2\pi R}\ln\left[\dfrac{d+W}{d}\right]$ (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

$$I = \frac{(4\pi \times 10^{-7}\ \mathrm{T \cdot m/A})(2.0\ \mathrm{A/s})(0.04\ \mathrm{m})}{2\pi(10\ \Omega)} \ln\left[\frac{0.03}{0.01}\right] = 1.8 \times 10^{-9}\ \mathrm{A}$$ (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.

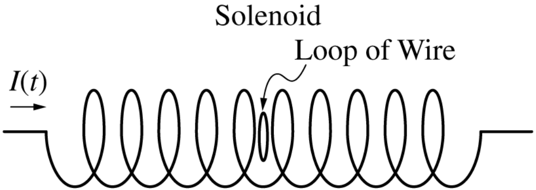
Question 3

(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?

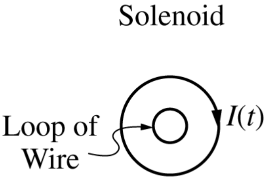
$C^{lockwise}{}_{C^{ounterclockwise}{}_{Z^{ero}}}$

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.]

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

(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.