Past-paper walk-through

Magnetic Flux ▪ 13.1

eXercise

Questions in this set

- 2026 Q4
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- 2019 Set 1 Q3
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- 2015 Q3
- 2014 Q2

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

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

(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.

[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

(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 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 $0, L, 2L, 3L, 4L$.]

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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 $x = 4.5L$).]

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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 $+\Phi$.

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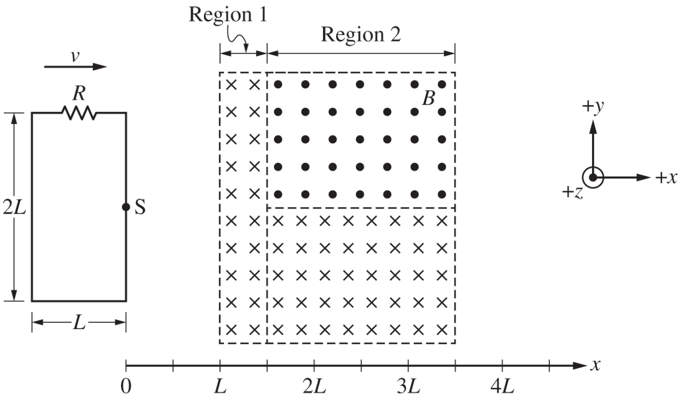

Figure 2

Question 3

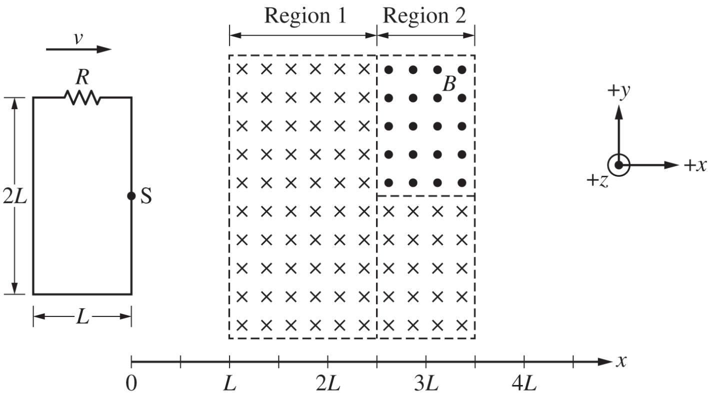

Figure 1

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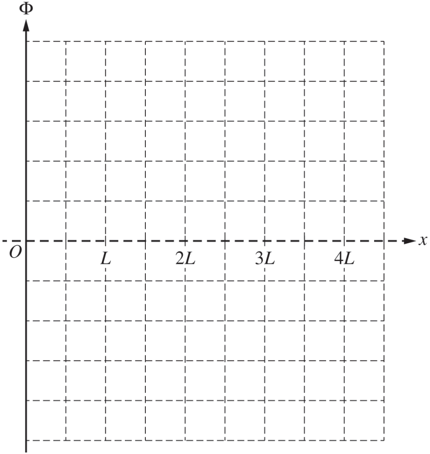

Question 3

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

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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.

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(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.

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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 $0, L, 2L, 3L, 4L$.]

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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}.

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[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.

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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.

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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 $P = \dfrac{(\Delta V)^2}{R}$ 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: $P = \dfrac{(2BLv)^2}{R} = \dfrac{4B^2L^2v^2}{R}$.

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.)

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2024 Set 2 ▪ Q3

[Figure 1: A diagram on the left shows a square loop of side length D approaching a rectangular field region from the left, with $+x$ to the right and $+y$ upward indicated by a small axis. The loop has a resistor R on its left side and width D, moving right with velocity v in the $+x$ direction. To the right is a number line marked $0, D, 2D, 3D, 4D$. Above the number line, two adjacent rectangular field regions are shown: "Region 1" spans from $x = D$ to $x = 2D$, containing an array of small circles with dots (field out of the page, magnitude B); "Region 2" spans from $x = 2D$ to $x = 3D$, containing an array of "$\times$" symbols (field into the page, magnitude $2B$). Point S is the leading (right) edge of the loop.]

A wire is connected to a resistor of resistance R to form a rigid square loop of side length D. 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 enters Region 1

Question 3

of external uniform magnetic field of magnitude B that is directed in the $+z$-direction. Region 1 has boundaries $x = D$ and $x = 2D$. The loop later enters Region 2 of external uniform magnetic field of magnitude $2B$ that is directed in the $-z$-direction. Region 2 has boundaries $x = 2D$ and $x = 3.5D$. Point S is the midpoint of the leading edge of the loop.

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

[Blank graph: vertical axis labeled Φ, horizontal axis labeled x with tick marks at D, $2D$, $3D$, $4D$, gridlines shown, origin labeled O. No curve plotted; axes are empty for the student to sketch.]

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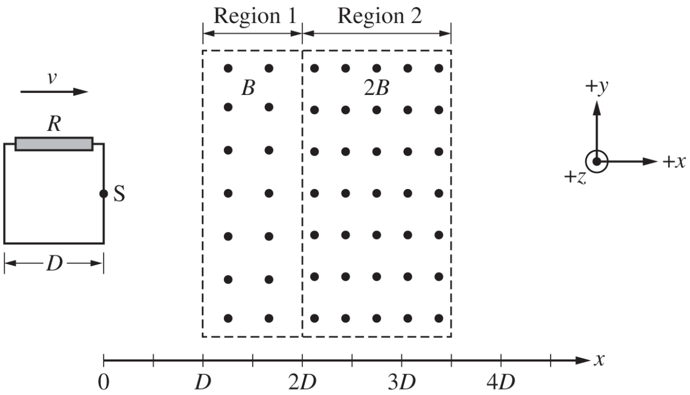

Figure 1

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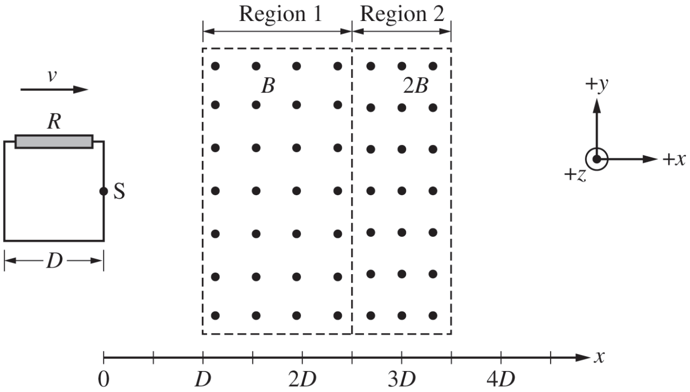

Figure 2

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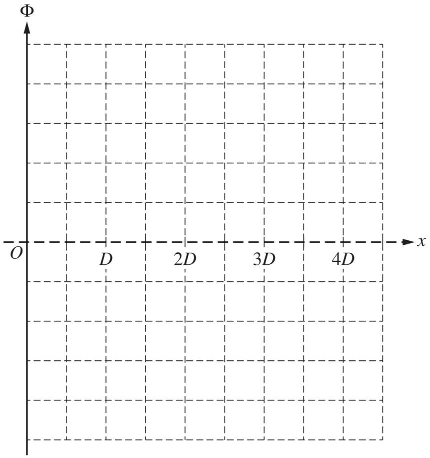

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2024 Set 2 ▪ Q3

[Figure 1: A diagram on the left shows a square loop of side length D approaching a rectangular field region from the left, with $+x$ to the right and $+y$ upward indicated by a small axis. The loop has a resistor R on its left side and width D, moving right with velocity v in the $+x$ direction. To the right is a number line marked $0, D, 2D, 3D, 4D$. Above the number line, two adjacent rectangular field regions are shown: "Region 1" spans from $x = D$ to $x = 2D$, containing an array of small circles with dots (field out of the page, magnitude B); "Region 2" spans from $x = 2D$ to $x = 3D$, containing an array of "$\times$" symbols (field into the page, magnitude $2B$). Point S is the leading (right) edge of the loop.]

A wire is connected to a resistor of resistance R to form a rigid square loop of side length D. 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 enters Region 1 of external uniform magnetic field of magnitude B that is directed in the $+z$-direction. Region 1 has boundaries $x = D$ and $x = 2D$. The loop later enters Region 2 of external uniform magnetic field of magnitude $2B$

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that is directed in the $-z$-direction. Region 2 has boundaries $x = 2D$ and $x = 3.5D$. Point S is the midpoint of the leading edge of the loop.

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

Indicate whether the current I_0 that is induced in the square loop when Point S reaches $x = 1.5D$ is clockwise, counterclockwise, or zero.

________ Clockwise ________ Counterclockwise ________ Zero

Briefly **justify** your answer.

(b)(ii) **Derive** an expression for I_0 when Point S reaches $x = 1.5D$. If $I_0 = 0$, indicate how the derived expression shows that $I_0 = 0$. Express your answer in terms of R, D, v, B, and physical constants, as appropriate.

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

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2024 Set 2 ▪ Q3

[Figure 1: A diagram on the left shows a square loop of side length D approaching a rectangular field region from the left, with $+x$ to the right and $+y$ upward indicated by a small axis. The loop has a resistor R on its left side and width D, moving right with velocity v in the $+x$ direction. To the right is a number line marked $0, D, 2D, 3D, 4D$. Above the number line, two adjacent rectangular field regions are shown: "Region 1" spans from $x = D$ to $x = 2D$, containing an array of small circles with dots (field out of the page, magnitude B); "Region 2" spans from $x = 2D$ to $x = 3D$, containing an array of "$\times$" symbols (field into the page, magnitude $2B$). Point S is the leading (right) edge of the loop.]

A wire is connected to a resistor of resistance R to form a rigid square loop of side length D. 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 enters Region 1 of external uniform magnetic field of magnitude B that is directed in the $+z$-direction. Region 1 has boundaries $x = D$ and $x = 2D$. The loop later enters Region 2 of external uniform magnetic field of magnitude $2B$

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that is directed in the $-z$-direction. Region 2 has boundaries $x = 2D$ and $x = 3.5D$. Point S is the midpoint of the leading edge of the loop.

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

The vertical boundary between regions 1 and 2 is now shifted, so the boundary is at $x = 2.5D$. After the boundary is shifted, the square 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 $x = 4.5D$ is E_{new}.

[Figure 2: Same layout as Figure 1, but the boundary between Region 1 (dots, field out of page, magnitude B) and Region 2 ($\times$'s, field into page, magnitude $2B$) is now at $x = 2.5D$; Region 1 spans $x = D$ to $x = 2.5D$, Region 2 spans $x = 2.5D$ to $x = 3.5D$ (approximately). Number line marked $0, D, 2D, 3D, 4D$. Square loop with resistor R and side length D shown at the left, moving in $+x$ direction with speed v.]

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Indicate whether E_{new} is greater than, less than, or equal to E_{original}.
$\text{E}_{\text{new}} > E_{\text{original}}$ $\text{E}_{\text{new}} < E_{\text{original}}$ $\text{E}_{\text{new}} = E_{\text{original}}$
Briefly **justify** your answer.

Question 3

2024 Set 2 ▪ Q3

[Figure 1: A diagram on the left shows a square loop of side length D approaching a rectangular field region from the left, with $+x$ to the right and $+y$ upward indicated by a small axis. The loop has a resistor R on its left side and width D, moving right with velocity v in the $+x$ direction. To the right is a number line marked $0, D, 2D, 3D, 4D$. Above the number line, two adjacent rectangular field regions are shown: "Region 1" spans from $x = D$ to $x = 2D$, containing an array of small circles with dots (field out of the page, magnitude B); "Region 2" spans from $x = 2D$ to $x = 3D$, containing an array of "$\times$" symbols (field into the page, magnitude $2B$). Point S is the leading (right) edge of the loop.]

A wire is connected to a resistor of resistance R to form a rigid square loop of side length D. 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 enters Region 1 of external uniform magnetic field of magnitude B that is directed in the $+z$-direction. Region 1 has boundaries $x = D$ and $x = 2D$. The loop later enters Region 2 of external uniform magnetic field of magnitude $2B$

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that is directed in the $-z$-direction. Region 2 has boundaries $x = 2D$ and $x = 3.5D$. Point S is the midpoint of the leading edge of the loop.

(d) The original magnetic fields are modified so that the region $D < x < 3.5D$ contains an external uniform magnetic field B that is directed in the $+z$-direction.

A new wire is connected to a resistor of resistance R to form a rigid triangular loop with base length D and height D, as shown in Figure 3. 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 upper-left corner of the loop.

[Figure 3: A right triangular loop with a resistor R on its vertical left side of height D, base length D along the bottom, and hypotenuse sloping from the top-left down to the bottom-right, with Point S marked at the top-left corner. The triangle moves in the $+x$ direction with speed v. To the right, a single rectangular field region spans from

Question 3

$x = D$ to $x = 3.5D$, filled with dots (field out of the page, magnitude B). Number line marked $0, D, 2D, 3D, 4D$, with small axis indicator showing $+x$ and $+z$ directions.]
On the following axes, **sketch** a graph of the induced current I_2 in the loop as Point S moves from $x = D$ to $x = 3D$.
[Blank graph: vertical axis labeled I_2, horizontal axis with tick marks at D, $2D$, $3D$, $4D$; shaded vertical bands appear at the far left (near 0–D) and in the middle region (around $2D$–$3D$) as reference/shading, with the rest of the axes empty for the student to sketch a curve.]

Solution 3

(a) Mark scheme

- Sketch of magnetic flux Φ vs. position x (from $x = 0$ to $x = 4.5D$): flux is zero until $x = D$; from $x = D$ to $x = 2D$, $|\Phi|$ increases with a constant slope; the curve continues smoothly (continuous slope, no kink) at $x = 2D$ and keeps increasing with that same slope until $x = 3D$; Φ is then constant and nonzero for $3D < x < 3.5D$; finally $|\Phi|$ decreases from that nonzero value at $x = 3.5D$ down to zero at $x = 4.5D$. (A graph reflected across the horizontal axis also earns full credit; only the magnitudes/shape of the slopes over the full regions $D < x < 3D$ and $3.5D < x < 4.5D$ matter, not their exact values.) 1 point each for: the initial linear rise from $x = D$ to $2D$; continuity with the same slope from $2D$ to $3D$; the

Solution 3

constant nonzero plateau from $3D$ to $3.5D$; the decrease from $3.5D$ to zero at $4.5D$.

Solution 3

(b)(i)

Mark scheme

- Clockwise. Justification: as Point S reaches $x = 1.5D$, the magnetic flux through the loop is increasing in the $+z$-direction. By Lenz's law, the induced current opposes this increase, so it creates a magnetic field in the $-z$-direction inside the loop; by the right-hand rule this requires the induced current to flow clockwise. 1 point for selecting Clockwise with an attempted relevant justification, 1 point for indicating the flux is increasing in $+z$ (or, alternately, that the induced current's own field points in $-z$).

Solution 3

(b)(ii) Mark scheme

- Apply Faraday's law: $\mathcal{E} = -\frac{d\Phi_B}{dt} = -\frac{d}{dt}(BA)$. Since the loop has side length D and moves at speed v, the area swept per unit time is $\frac{dA}{dt} = Dv$, giving $\mathcal{E} = -B\frac{dA}{dt} = -BDv$. By Ohm's law, $I_S = \mathcal{E}/R$, so $I_0 = I_S = -\frac{BDv}{R}$ (magnitude BDv/R). 1 point for a multistep derivation that includes Faraday's law, 1 point for indicating $dA/dt = Dv$, 1 point for using Ohm's law to get an expression for I_S consistent with the derived emf (negative sign not required for any of the three points).

Solution 3

(b)(iii)

Mark scheme

- Use a correct general power expression, e.g. $P = I^2 R$, and substitute the current found in part (b)(ii), $I_S = -BDv/R$: $P = \left(-\frac{BDv}{R}\right)^2 R = \frac{B^2 D^2 v^2}{R}$. 1 point for using a correct general expression for P ($P = I^2 R$, $P = (\Delta V)^2/R$, or $P = I\Delta V$), 1 point for an expression for P consistent with the part (b)(ii) result, expressed only in terms of R, D, v, B (and constants).

Solution 3

(c) Mark scheme

- $E_{\text{new}} = E_{\text{original}}$. Justification: the total change in magnetic flux through the loop over the full transit (from $x = 0$ to $x = 4.5D$) is the same in both scenarios — shifting the region boundary only changes when the flux changes, not how much it changes overall — so the induced emf and current profile produce the same total energy dissipated by the resistor in both cases. 1 point for selecting $E_{\text{new}} = E_{\text{original}}$ with an attempted justification, 1 point for indicating one of: the change in magnetic flux is the same for both scenarios / the induced current occurs for the same total time in both scenarios / the induced emf occurs for the same total time in both scenarios.

Solution 3

(d) Mark scheme

- Sketch of induced current magnitude I_T in the new triangular loop as it moves through the field region $D < x < 3.5D$ (only the region $x = D$ to $x = 3D$ is scored): $|I_T|$ starts at a nonzero value at $x = D$ and only decreases (no local increase) until it reaches zero at $x = 2D$ (as the triangle's widening base continues sweeping into the uniform field, the rate of flux change — and hence the induced current — decreases as the loop approaches being fully inside the field). I_T is then zero from $x = 2D$ to $x = 3D$, since the loop is entirely within the uniform field there and the flux through it is constant. (A graph reflected across the horizontal axis also earns full credit; portions before $x = D$ or after $x = 3D$ are not scored.) 1

Solution 3

point for a sketch whose absolute value only decreases from $x = D$ to $x = 2D$, 1 point for a sketch that is zero from $x = 2D$ to $x = 3D$.

Question 3

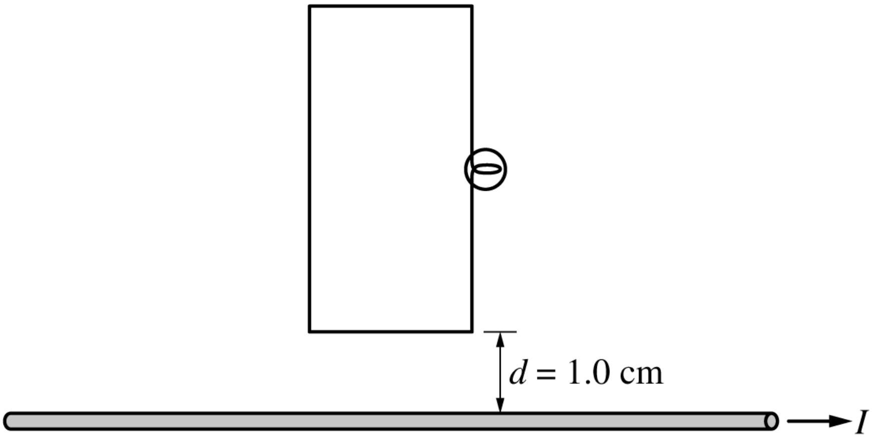
2022 Set 1 ▪ Q3

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.]

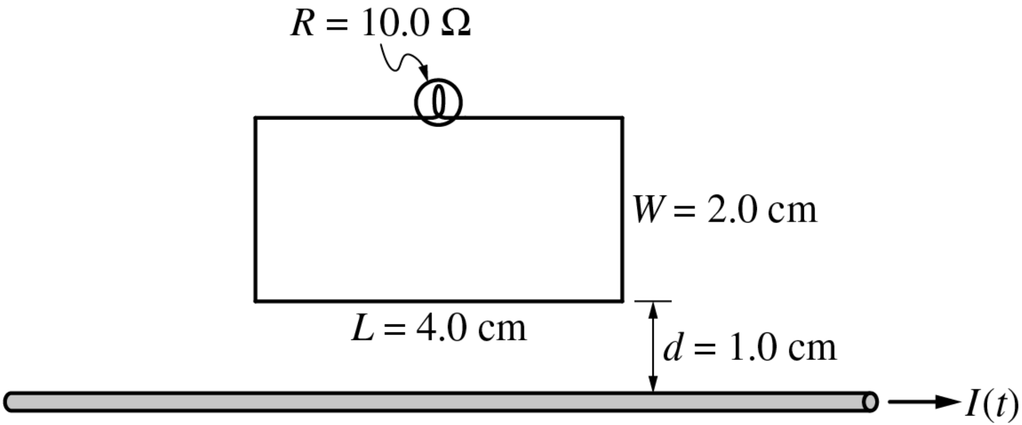
Question 3

(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 $B = \frac{\mu_0 I}{2\pi r}$ (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): $\Phi_B = \int_d^{d+W} \frac{\mu_0 IL}{2\pi r}\, dr = \frac{\mu_0 IL}{2\pi} \ln\left[\frac{d+W}{d}\right]$ (1 pt:

Solution 3

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

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

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

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

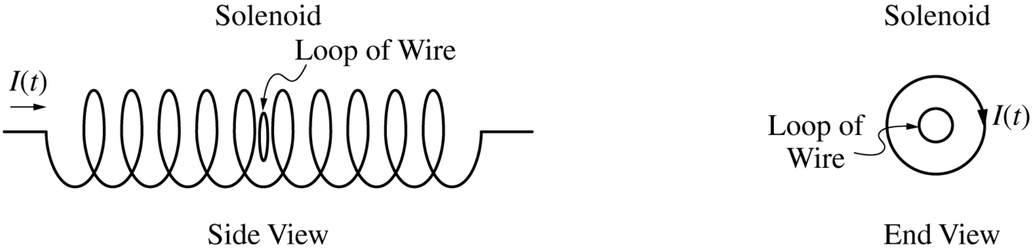
Question 3

(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



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.]

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

(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.