2024

AP

AP® Physics C: Electricity and Magnetism

Sample Student Responses and Scoring Commentary Set 1

Inside:

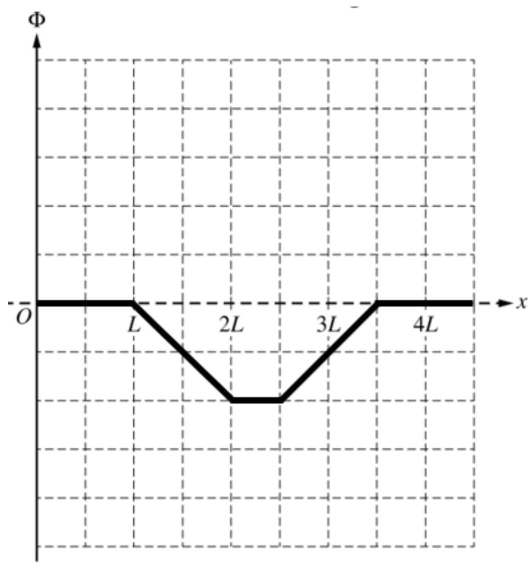
Free-Response Question 3

- ☑ Scoring Guidelines
- ☑ Student Samples
- ☑ Scoring Commentary

Question 3: Free-Response Question — 15 points

(a)	For a sketch that indicates that the magnetic flux is zero from $x = 0$ to $x = L$ and for the region $x > 3.5L$	**1 point**
	For a sketch that indicates that the absolute value of the magnetic flux increases with a constant slope in the region $L < x < 2L$	**1 point**
	For a sketch that indicates that the magnetic flux is constant and nonzero in the region $2L < x < 2.5L$	**1 point**
	For a sketch that indicates that the absolute value of the magnetic flux decreases from a nonzero value at $x = 2.5L$ to zero at $x = 3.5L$	**1 point**

Example Response



Scoring Note: A sketch that is reflected across the horizontal axis can earn the four points.
Scoring Note: The absolute values of the slopes in regions $L < x < 2D$ and $2.5L < x < 3.5L$ are not considered for earning points in the response in part (a).

Total for part (a) 4 points

(b)(i)	For selecting Counterclockwise with an attempt at a relevant justification	**1 point**
	For indicating the magnetic flux through the loop is increasing in the $-z$-direction **OR** For indicating the magnetic field due to the induced current will be directed in the $+z$-direction	**1 point**

Example Response

Counterclockwise. The magnetic flux through the loop is increasing in the $-z$-direction. Therefore, a magnetic field is induced by the current in the loop to oppose the increasing magnetic flux. To establish this field, the current must be counterclockwise.

(b)(ii) For a multistep derivation that includes Faraday's law **1 point**

Scoring Note: The point can be earned if a negative sign is not included.

Example Response

$$\mathcal{E} = -\frac{d\Phi_B}{dt} = -\frac{d}{dt}(BA)$$

For indicating $\frac{dA}{dt}$ is $2Lv$ **1 point**

Scoring Note: The point can be earned if a negative sign is included.

Example Response

$$\mathcal{E} = B\frac{dA}{dt} = 2BLv$$

For using Ohm's law, resulting in an expression for I_R that is consistent with the expression determined for the emf $\mathcal{E}$ **1 point**

Scoring Note: The point can be earned if a negative sign is included.

Example Response

$$I_R = \frac{2BLv}{R}$$

Example Solution

$$\mathcal{E} = -\frac{d\Phi_B}{dt}$$

$$\mathcal{E} = -\frac{d}{dt}\left(\int \vec{B} \cdot d\vec{A}\right)$$

$$\mathcal{E} = -\frac{d}{dt}(BA) = -\frac{d}{dt}(-B(2L)x)$$

$$\mathcal{E} = 2BL\frac{dx}{dt}$$

$$\mathcal{E} = 2BLv$$

$$I = \frac{\Delta V}{R}$$

$$I_R = \frac{\mathcal{E}}{R}$$

$$I_R = \frac{2BLv}{R}$$

(b)(iii)	For using a correct general expression for P	**1 point**

Example Responses

$P = I^2R$ **OR** $P = \frac{(\Delta V)^2}{R}$ **OR** $P = I\Delta V$

For an expression for P that is consistent with the response in part (b)(ii) that is in terms of the provided quantities only — **1 point**

Example Response

$$P = \frac{4B^2L^2v^2}{R}$$

Example Solution

$$P = I^2R$$

$$P = \frac{(2BLv)^2}{R}$$

$$P = \frac{4B^2L^2v^2}{R}$$

Total for part (b) 7 points

(c)	For selecting $E_{\text{new}} < E_{\text{original}}$ with an attempt at a relevant justification	**1 point**

For indicating one of the following: — **1 point**

- 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.
- The induced emf occurs for a greater amount of time in the original scenario.

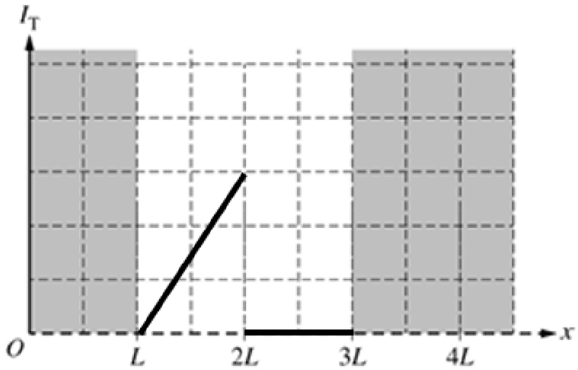
Example Response

The change in magnetic flux is greater in the original scenario, which produces an emf *and current for a longer time. Therefore,* $E_{\text{new}} < E_{\text{original}}$.

Total for part (c) 2 points

(d)	For a sketch that has an absolute value that only increases from $x = L$ to $x = 2L$	**1 point**
	For a sketch that is zero from $2L$ to $3L$	**1 point**

Example Response



Scoring Note: A response that is reflected across the horizontal axis earns both points.
Scoring Note: Any portion of the graph before $x = L$ and after $x = 3L$ are not scored.

Total for part (d) 2 points

Total for question 3 15 points

Question 3

Begin your response to **QUESTION 3** on this page.

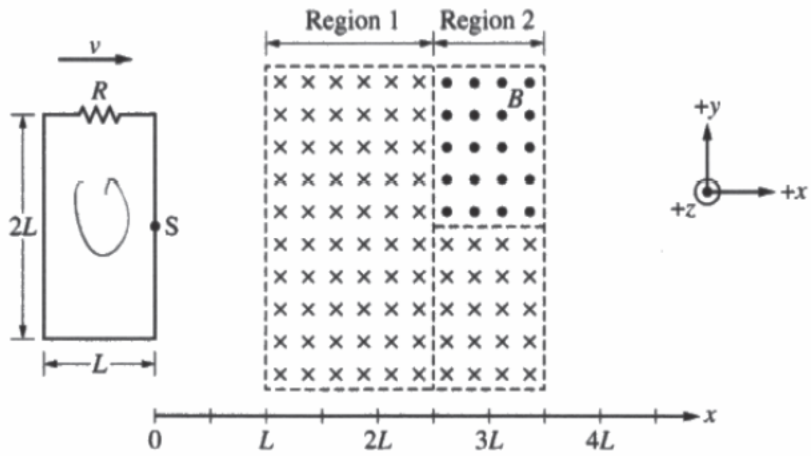


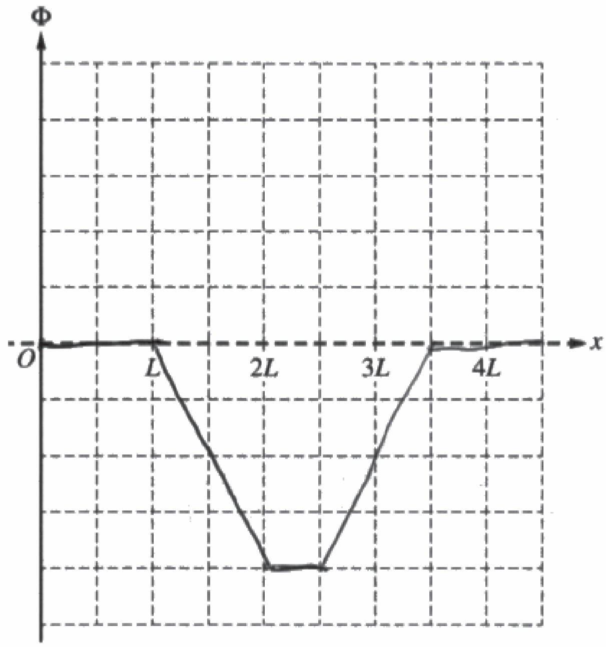
Figure 1

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 then 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 $x = 2.5L$. The loop later enters Region 2 with two external, uniform magnetic fields, each of magnitude B, that are parallel but are directed in opposite z-directions. Region 2 has boundaries $x = 2.5L$ and $x = 3.5L$. Point S is the midpoint of the leading edge of the loop and is aligned with the horizontal boundary in Region 2 that separates the two magnetic fields.

Question 3

Continue your response to **QUESTION 3** on this page.

(a) 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 $+\Phi$.



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

i. **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   X Counterclockwise   ____ Zero

Briefly **justify** your answer.

As the loop ~~as~~ enters the region of magnetic field directed into the page, the flux becomes increasingly negative. Nature wants to oppose this (Lenz's law), so the induced ~~emf should~~ current should produce ~~fo~~ magnetic fields directed out of the page, which corresponds to a counterclockwise current.

Question 3

Continue your response to **QUESTION 3** on this page.

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.

$\Phi_B = NBA \qquad N = 1$

$\mathcal{E} = -\frac{d\Phi_B}{dt} = -NB\frac{dA}{dt} = -B(2L)v$

$V = IR = |\mathcal{E}|$

$\Rightarrow I_R = \frac{|\mathcal{E}|}{R} = \frac{2BLv}{R}$

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.

~~$P = \left(\frac{2BLv}{R}\right)$~~

$P = I^2 R = \left(\frac{2BLv}{R}\right)^2 R = \frac{4B^2L^2v^2}{R}$

  GO ON TO THE NEXT PAGE.

Question 3

Continue your response to QUESTION 3 on this page.

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}.

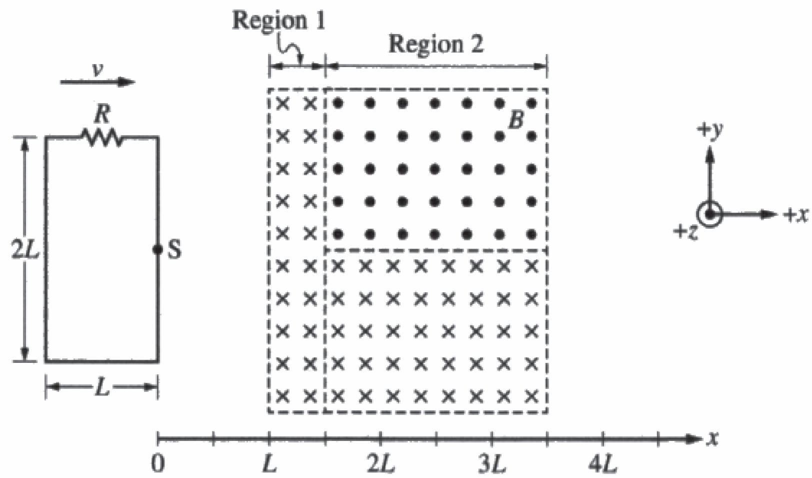


Figure 2

(c) **Indicate** whether E_{new} is greater than, less than, or equal to $E_{original}$.

____ $E_{new} > E_{original}$ _X_ $E_{new} < E_{original}$ ____ $E_{new} = E_{original}$

Briefly justify your answer.

Energy is only dissipated when there is a change in magnetic flux, since that is required to induce a current in the loop. In the new situation, the magnetic flux is only changing from L to $\frac{5}{2}L$. However, in the old situation, the flux was changing from L to 2L and $\frac{5}{2}L$ to $\frac{7}{2}L$. Since the velocity is constant, the old situation has a change in magnetic flux for the longer time, so the energy dissipated in the original situation is greater than the new situation.

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Question 3

Continue your response to **QUESTION 3** on this page.

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.

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.

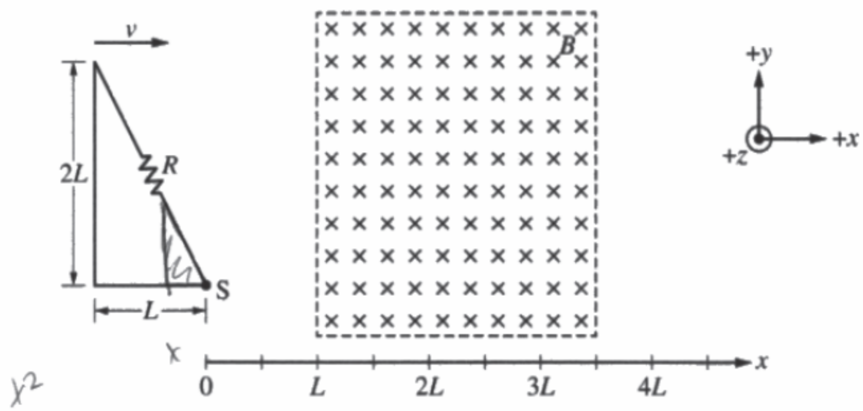
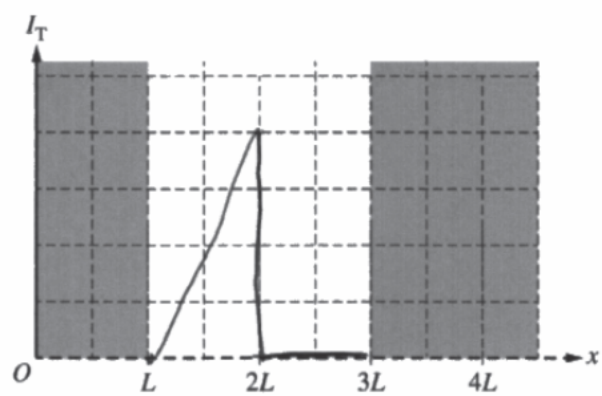


Figure 3

(d) On the following axes, **sketch** a graph of the induced current I_T in the triangular loop as Point S moves from $x = L$ to $x = 3L$.



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Question 3

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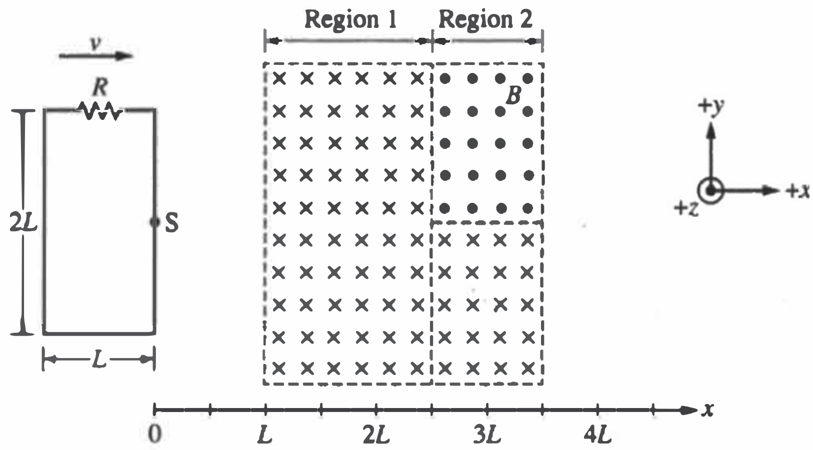

Figure 1

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 then 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 $x = 2.5L$. The loop later enters Region 2 with two external, uniform magnetic fields, each of magnitude B, that are parallel but are directed in opposite z-directions. Region 2 has boundaries $x = 2.5L$ and $x = 3.5L$. Point S is the midpoint of the leading edge of the loop and is aligned with the horizontal boundary in Region 2 that separates the two magnetic fields.

$$-\frac{d\phi}{dt} = -(2L)(v)$$

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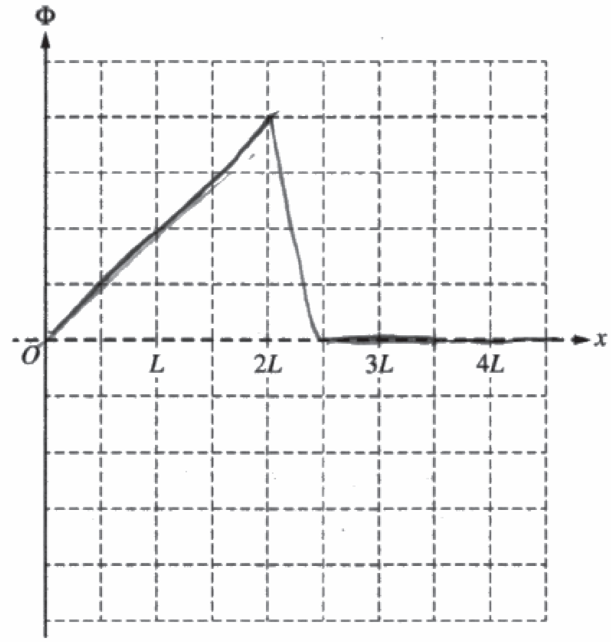
Question 3

Continue your response to **QUESTION 3** on this page.

(a) 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 $+\Phi$.



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

i. **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 X Counterclockwise ____ Zero

Briefly **justify** your answer.

According to Lenz's ~~right~~ left hand rule because flux is increasing

Question 3

Continue your response to **QUESTION 3** on this page.

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.

$$\varepsilon = \frac{-d\phi}{dt} = \frac{-dA}{dt}B = -2LvB$$

$$I = \frac{\varepsilon}{R} = \frac{-2LvB}{R}$$

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.

$$P = I^2R = \left(\frac{2LvB}{R}\right)^2 R$$

$$= \frac{4L^2v^2B^2}{R^2} R$$

$$P = \frac{4L^2v^2B^2}{R}$$

GO ON TO THE NEXT PAGE.

Question 3

Continue your response to **QUESTION 3** on this page.

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}.

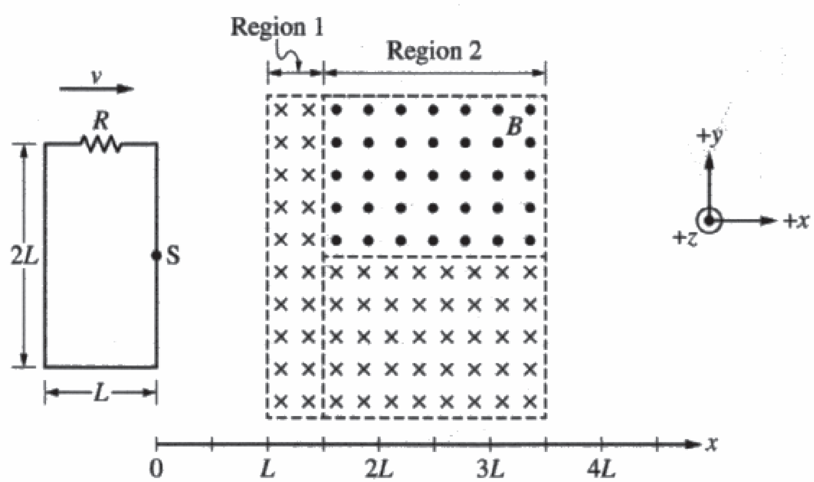


Figure 2

(c) **Indicate** whether E_{new} is greater than, less than, or equal to $E_{original}$.

____ $E_{new} > E_{original}$ ____ $E_{new} < E_{original}$ X $E_{new} = E_{original}$

Briefly **justify** your answer.

The same amount of work is done on the circuit by the magnetic forces

Question 3

Continue your response to **QUESTION 3** on this page.

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.

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.

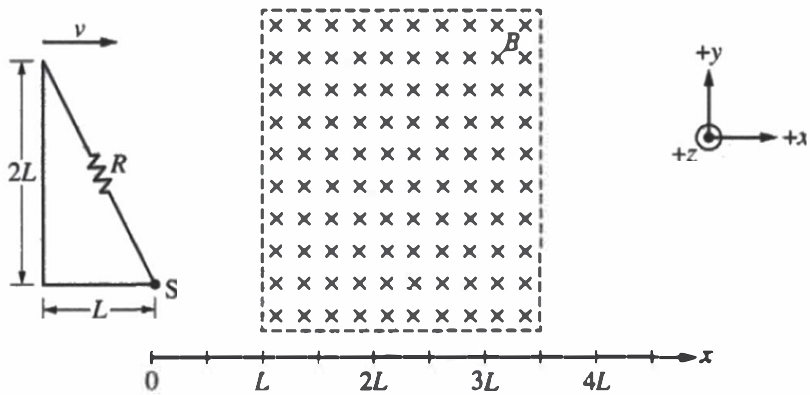
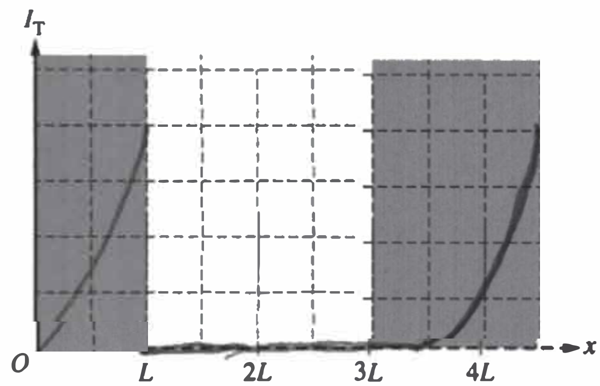


Figure 3

(d) On the following axes, **sketch** a graph of the induced current I_T in the triangular loop as Point S moves from $x = L$ to $x = 3L$.

$\frac{d\Phi}{dt} \uparrow$ $\varepsilon \uparrow$



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Question 3

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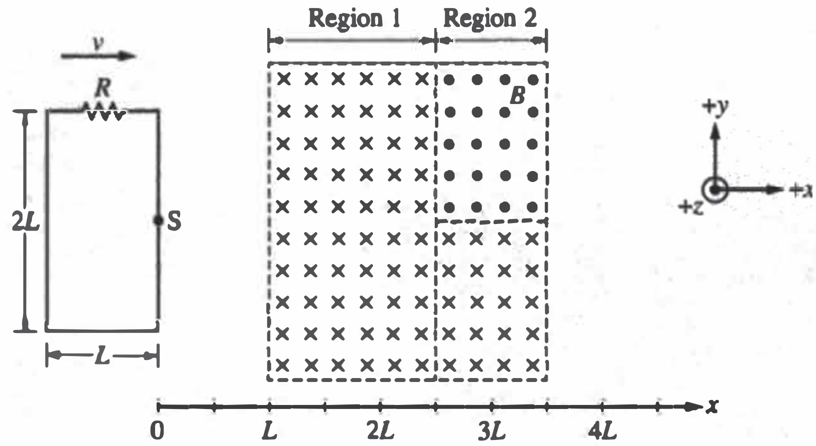


Figure 1

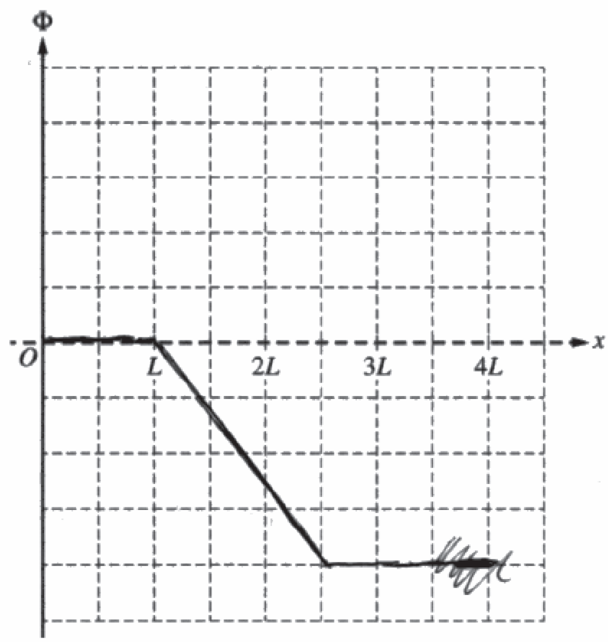
3. A wire is connected to a resistor of resistance R to form a rigid rectangular loop of width L and height $2L$. An external force is exerted on the loop so that the loop always moves with constant speed v in the $+x$-direction, as shown in Figure 1. The loop then enters Region 1 of external uniform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

GO ON TO THE NEXT PAGE.

Question 3

Continue your response to **QUESTION 3** on this page.

(a) 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 $+\Phi$.



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

i. **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.

Right hand rule

Question 3

Continue your response to **QUESTION 3** on this page.

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.

$I = \frac{\Delta V}{R}$

$\oint B \cdot dl = \mu_0 I$

$I = Nev_d A$

$\frac{BL}{\mu_0} = I_R$

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.

$P = I \Delta V$

Question 3

Continue your response to **QUESTION 3** on this page.

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}.

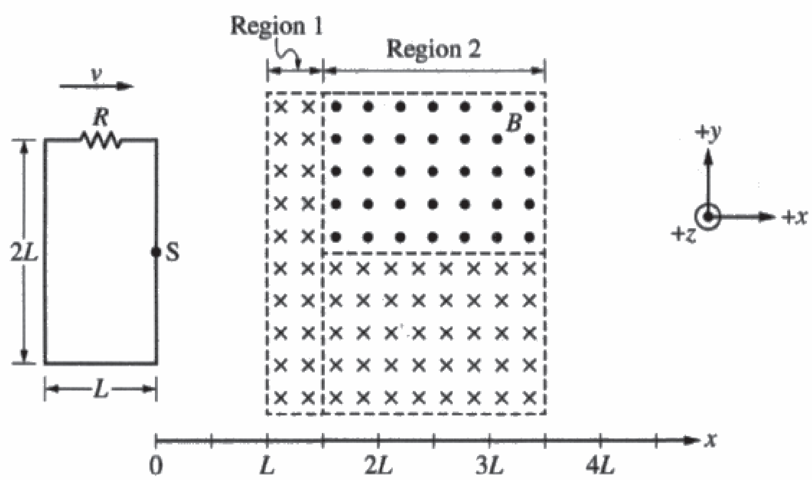


Figure 2

(c) **Indicate** whether E_{new} is greater than, less than, or equal to $E_{original}$.

____ $E_{new} > E_{original}$ ____ $E_{new} < E_{original}$ ✓ $E_{new} = E_{original}$

Briefly **justify** your answer.

Conservation of energy, no energy lost in system

Question 3

Continue your response to QUESTION 3 on this page.

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.

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.

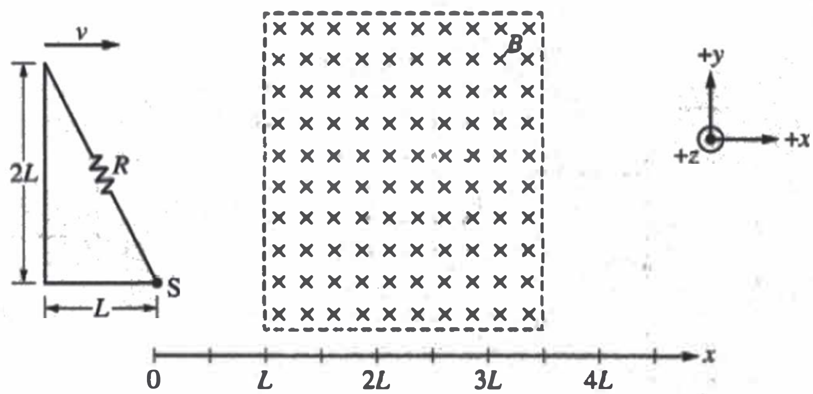
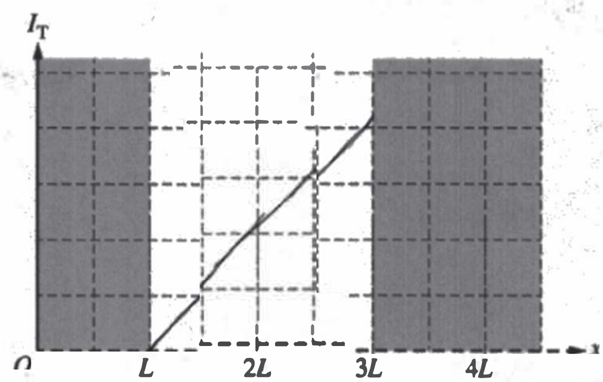


Figure 3

(d) On the following axes, **sketch** a graph of the induced current I_T in the triangular loop as Point S moves from $x = L$ to $x = 3L$.



Question 3

Note: Student samples are quoted verbatim and may contain spelling and grammatical errors.

Overview

The responses were expected to demonstrate the ability to:

- Graphically represent the magnetic flux for a square loop of wire as it enters a region containing a single magnetic field and then a region containing two magnetic fields in opposing directions.
- Determine and justify the direction of induced current due to a changing magnetic flux.
- Derive an expression for induced current in a square loop of wire using Faraday's law and Ohm's law.
- Derive an expression for power dissipated by a resistor due to an induced current.
- Compare and justify the differences in energy dissipation for a moving loop of wire through a different scenario of magnetic fields.
- Graphically represent the induced current due to a triangular loop of wire entering a uniform magnetic field.

Sample: 3A
Score: 15

Part (a) earned 4 points. The first point was earned for indicating that the magnetic flux is zero from $x = 0$ to $x = L$ and for $x = 3.5L$. The second point was earned for indicating that the absolute value of the magnetic flux increases with a constant slope in the region $L < x < 2L$. The third point was earned for indicating that the magnetic flux is constant and nonzero in the region $2L < x < 2.5L$. The fourth point was earned for indicating that the absolute value of the magnetic flux decreases from a nonzero value at $x = 2.5L$ to zero at $x = 3.5L$. Part (b) earned 7 points. The first point was earned for selecting a counterclockwise direction with an attempt at a relevant justification. The second point was earned for indicating that the magnetic flux through the loop is increasing into the page (the $-z$-direction). The third point was earned because the response consists of a multi-step derivation that includes Faraday's law. The fourth point was earned for indicating that $\frac{dA}{dt} = 2Lv$. The fifth point was earned for using Ohm's law resulting in an expression for I_R that is consistent with the expression determined for $\mathcal{E}$. The sixth point was earned for using a correct general expression for P. The seventh point was earned for showing an expression for P that is consistent with the response in part (b)(ii) and is in terms of the provided quantities only. Part (c) earned 2 points. The first point was earned for selecting $E_{\text{new}} < E_{\text{original}}$ with an attempt at a relevant justification. The second point was earned for indicating that the change in magnetic flux is greater in the original scenario. Part (d) earned 2 points. The first point was earned because the response has a sketch with an absolute value that only increases from $x = L$ to $x = 2L$. The second point was earned because the response has a sketch that is zero from $x = 2L$ to $x = 3L$.

Question 3 (continued)

Sample: 3B
Score: 8

Part (a) earned 1 point. The first point was not earned because the response correctly indicates that the magnetic flux is zero in the region $x > 3.5L$, but the sketch incorrectly shows nonzero values for the region $0 < x < L$. The second point was earned for indicating that the absolute value of the magnetic flux increases with a constant slope in the region $L < x < 2L$. The third point was not earned because the response shows that the absolute value of the magnetic flux decreases in the region $2L < x < 2.5L$ instead of a constant nonzero value. The fourth point was not earned because the response incorrectly indicates that the magnetic flux is zero for $2.5L > x > 3.5L$ instead of decreasing from a nonzero value at $x = 2.5L$ to a zero value at $x = 3.5L$. Part (b) earned 6 points. The first point was earned for selecting a counterclockwise direction with an attempt at a relevant justification. The second point was not earned because the response does not mention the changing magnetic flux directed into the page ($-z$-direction) or the induced magnetic field directed out of the page (the $+z$-direction). The third point was earned for including Faraday's law as part of a multi-step derivation. The fourth point was earned for indicating that $\frac{dA}{dt} = 2Lv$. The fifth point was earned for using Ohm's law resulting in an expression for I_R that is consistent with the expression determined for $\mathcal{E}$. The sixth point was earned for using a correct general expression for P. The seventh point was earned because the response has an expression for P that is consistent with the response in part (b)(ii) and is in terms of the provided quantities only. Part (c) did not earn any points. The first point was not earned because while there is an attempt at a relevant justification, the response does not select $E_{new} < E_{original}$. The second point was not earned because the response does not state that the change in magnetic flux is greater in the original scenario or that the induced current occurs for a greater amount of time in the original scenario. Part (d) earned 1 point. The first point was not earned because the response indicates zero current from $x = L$ to $x = 2L$ instead of increasing current for the same region. The second point was earned because the response has zero current from $x = 2.5L$ to $x = 3L$.

Question 3 (continued)

Sample: 3C
Score: 3

Part (a) earned 1 point. The first point was not earned because while the response indicates that the magnetic flux is zero from $x = 0$ to $x = L$, the sketch does not have a value for $x > 3.5L$. The second point was earned for indicating that the absolute value of the magnetic flux increases with a constant slope in the region $L < x < 2L$. The third point was not earned because the response has an increasing magnetic flux, instead of being constant and nonzero in the region $2L < x < 2.5L$. The fourth point was not earned because the response indicates a constant nonzero value from $x = 2.5L$ to $x = 3.5L$ instead of decreasing to zero. Part (b) earned 1 point for selecting a counterclockwise direction with an attempt at a relevant justification. The second point was not earned because while the response states the "right-hand rule," it is not specific in referencing the direction of the change in magnetic flux or the induced field. The third point was not earned because the response does not include Faraday's law. The fourth point was not earned because the response does not indicate $\frac{dA}{dt} = 2Lv$. The fifth point was not earned because while Ohm's law is stated, the response does not use the equation to result in an expression for I_R. The sixth point was not earned because while an equation for P is stated, the response does not use it as part of a derivation. The seventh point was not earned because the response does not have a substituted expression for P in terms of the provided quantities. Part (c) did not earn any points. The first point was not earned because while a justification was made, the response does not select $E_{\text{new}} < E_{\text{original}}$. The second point was not earned because the response does not indicate how the new scenario affects the change in flux or the time spent in the field. Part (d) earned 1 point because the response has a sketch with an absolute value that only increases from $x = L$ to $x = 2L$. The second point was not earned because the response has a sketch that is increasing from $x = 2L$ to $x = 3L$ instead of a constant zero value.