2024

AP

AP® Physics C: Electricity and Magnetism

Sample Student Responses and Scoring Commentary Set 2

Inside:

Free-Response Question 3

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

Question 3: Free-Response Question — 15 points

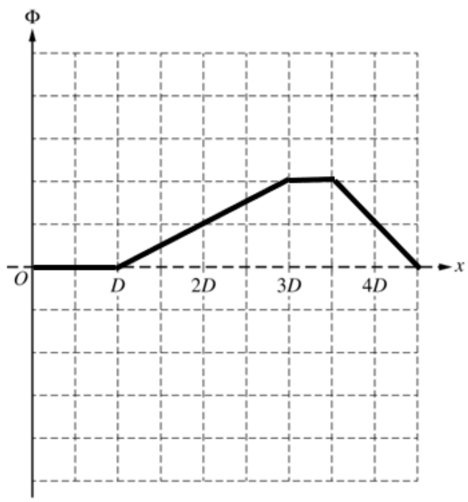
(a) For a sketch that indicates that the absolute value of the magnetic flux increases from zero at $x = D$ with a constant slope until $x = 2D$ — **1 point**

For a sketch that is continuous at $x = 2D$ and the absolute value of the magnetic flux increases until $x = 3D$ with the same slope as the slope in the region $D < x < 2D$ — **1 point**

For a sketch that indicates that the magnetic flux is constant and nonzero in the region $3D < x < 3.5D$ — **1 point**

For a sketch that indicates that the absolute value of the magnetic flux decreases from a nonzero value at $x = 3.5D$ to zero at $x = 4.5D$ — **1 point**

Example Response



Scoring Note: A response that is reflected across the horizontal axis can earn the four points.
Scoring Note: The absolute values of the slopes in the <u>entire</u> regions $D < x < 3D$ and $3.5D < x < 4.5D$ are not considered for earning these points.

Total for part (a) — **4 points**

(b)(i) For selecting Clockwise with an attempt at a relevant justification — **1 point**

For indicating the magnetic flux through the loop is increasing in the $+z$ -direction — **1 point**

OR

For indicating the magnetic field due to the induced current will be directed in the $-z$ -direction

Example Response

Clockwise. 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 clockwise.

(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 Dv **1 point**

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

Example Response

$$\mathcal{E} = -B\frac{dA}{dt} = -BDv$$

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

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

Example Response

$$I_S = -\frac{BDv}{R}$$

Example Solution

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

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

$$\mathcal{E} = -\frac{d}{dt}(BA) = -\frac{d}{dt}(B(D)x) = -BD\frac{dx}{dt}$$

$$\mathcal{E} = -BDv$$

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

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

$$I_S = -\frac{BDv}{R}$$

(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 power that is consistent with the response in part (b)(ii) that is in terms of the provided quantities only	**1 point**

Example Response

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

Example Solution

$$P = I^2R$$

$$P = \left(-\frac{BDv}{R}\right)^2 R$$

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

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 the same for both scenarios.
- The induced current occurs for the same amount of time for all transitions.
- The induced emf occurs for the same amount of time for all transitions

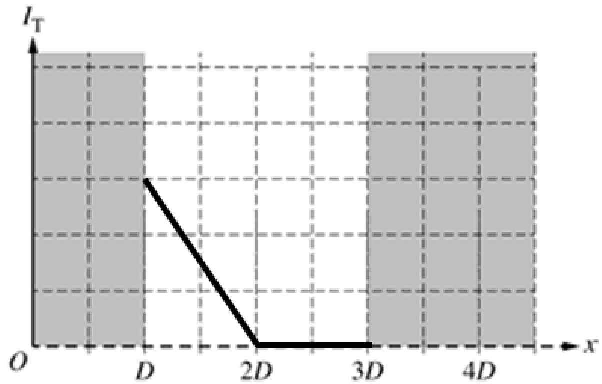
Example Response

The change in magnetic flux in the original scenario is the same as the new scenario, which produces an emf *and current that are the same in both scenarios. Therefore,* $E_{\text{new}} = E_{\text{original}}$

Total for part (c) 2 points

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

Example Response



Scoring Note: A response that is reflected across the horizontal axis can earn both points.

Scoring Note: Any portion of the graph before $x = D$ and after $x = 3D$ will not be scored.

Total for part (d) 2 points

Total for question 3 15 points

Question 3

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

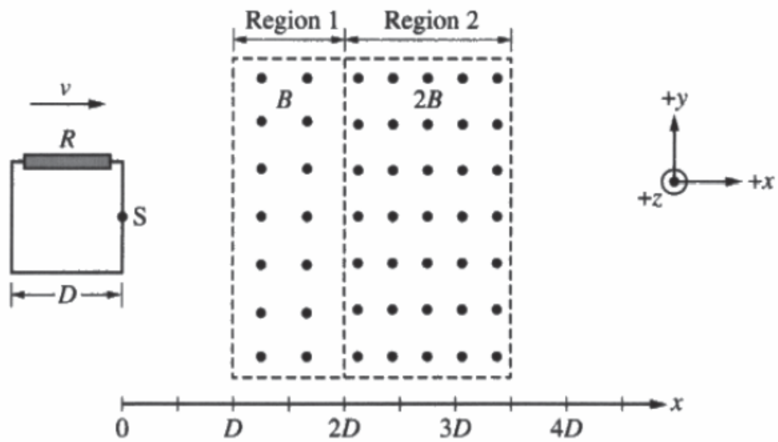


Figure 1

3. A wire is connected to a resistor of resistance R to form a rigid 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 then 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 $2B$ 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.

Question 3

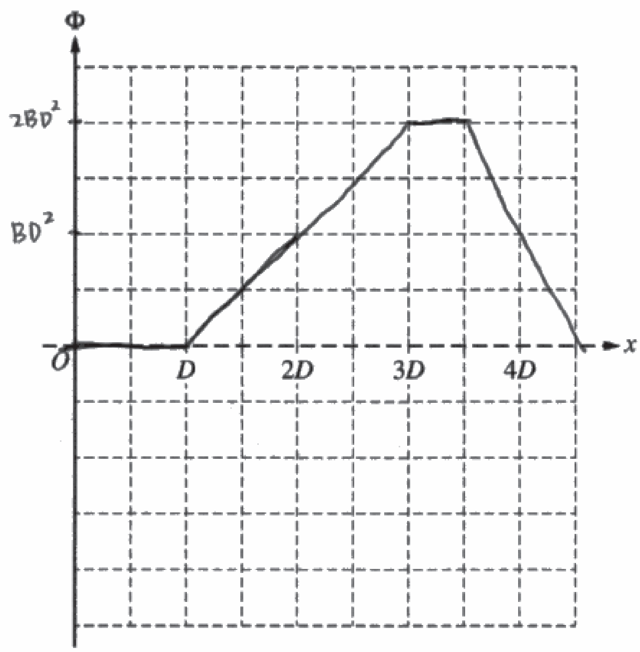
Continue your response to **QUESTION 3** on this page.

(a) On the following axes, **sketch** a graph of the magnetic flux Φ through the 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 $+\Phi$.

$A = D^2$

$\Phi|_{2D} = BA = BD^2$

$\Phi|_{3D} = 2BD^2$



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

i. **Indicate** whether the current I_S 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.

$\vec{B}$ ⊙ increases through the area, therefore induced $\vec{B}$ points ⊗. using the right hand rule, current flows clockwise

GO ON TO THE NEXT PAGE.

Question 3

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

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

const

$\Phi = BA\cos\theta \qquad \cos\theta = 1$

$= B(Dx)$

$\varepsilon = -\frac{d\Phi}{dt} = -B\frac{dA}{dt} = -BD\frac{dx}{dt} = -BDV$

$I = \frac{\varepsilon}{R} = \boxed{\frac{-BDV}{R}}$

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.

$I = -\frac{BDV}{R}$

$\varepsilon = -BDV$

$P = I\Delta V = \boxed{\frac{B^2D^2v^2}{R}}$

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Question 3

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

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 to $x = 2.5D$. 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}.

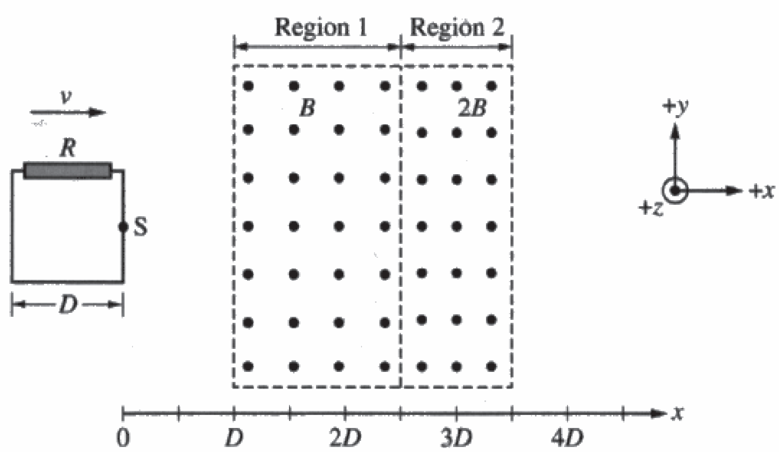


Figure 2

(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.

ℰ only induces when there is a change in flux, meaning that the loop travelling longer in region 1 does not result in any change.

The loop still enters region 1 with same velocity, enters region 2 with same velocity, and leaves region 2 with same velocity, making E_{new} and $E_{original}$ identical.

Question 3

Continue your response to QUESTION 3 on this page.

The original magnetic fields are modified so that the region $D < x < 3.5D$ 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 D and height D. 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-leading corner of the loop.

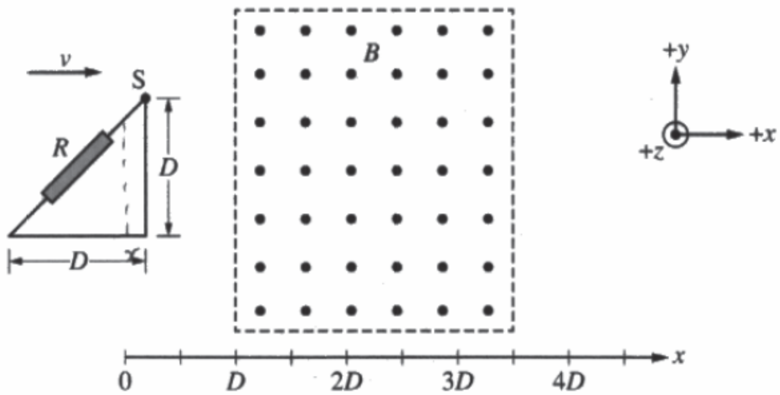


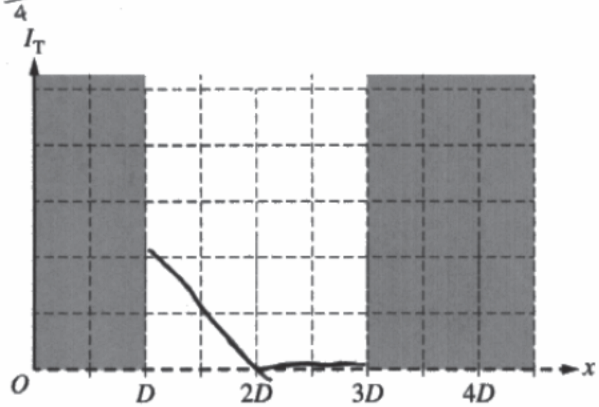
Figure 3

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

$$A = \frac{\left(x \cdot \frac{\sqrt{2}}{2} + D\right)x}{2} = \frac{\sqrt{2}x^2}{4} + \frac{Dx}{2}$$

$$\frac{dA}{dt} = \left(\frac{\sqrt{2}}{2}x + \frac{D}{2}\right)v$$

$$\varepsilon = vB\left(\frac{\sqrt{2}}{2}x + \frac{D}{2}\right)$$



Question 3

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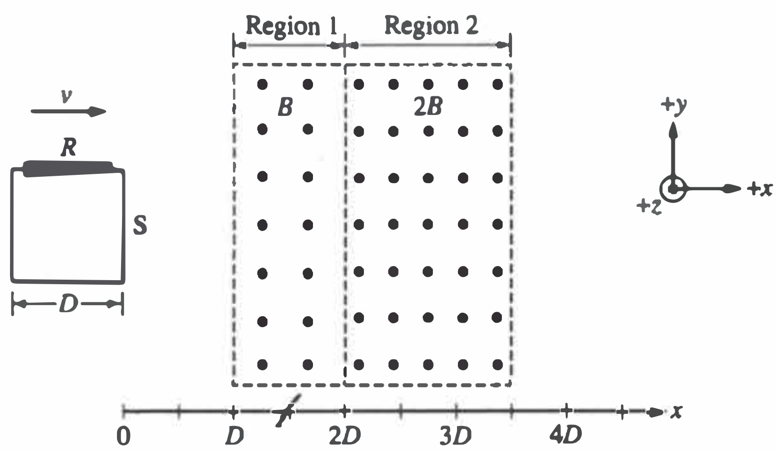


Figure 1

3. 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 then 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 $2B$ 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.

$\oint \vec{B} \cdot d\vec{A} = \oint B\,dA = B \oint dA = BD$

$dA = D\,dx$

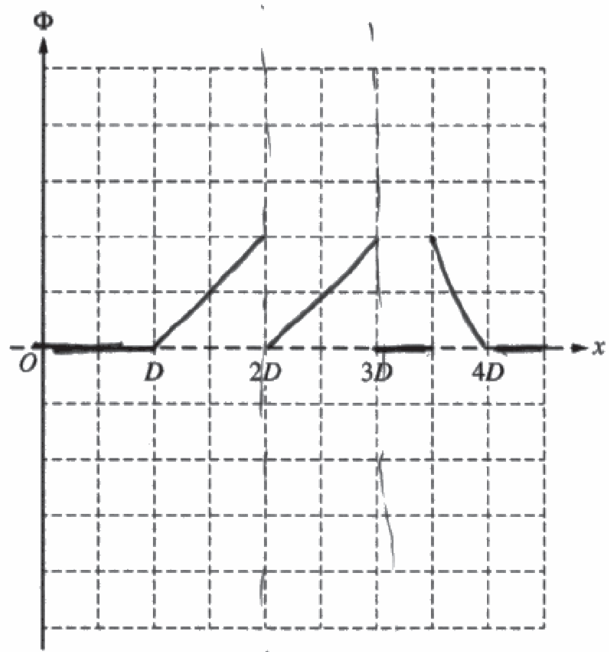
$\oint \vec{B} \cdot d\vec{A} \Rightarrow BDv$

$2BDv$

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 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 $+\Phi$.



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

i. **Indicate** whether the current I_S 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.

The magnetic field is out of the loop and the loop wants to restore itself to oppose the change in flux, so it generates CW current to create magnetic field into the loop to counteract the external magnetic field.

Question 3

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

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

$$|\mathcal{E}| = \frac{d\Phi_B}{dt} = \frac{d(BDx)}{dt} = BDv$$

$$\mathcal{E} = I_s R \rightarrow I_s = \mathcal{E}/R = \boxed{\frac{BDv}{R}}$$

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.

$$P = I^2 R = \left(\frac{BDv}{R}\right)^2 R = \frac{B^2D^2v^2}{R^{\not 2}} \not R$$

$$= \boxed{\frac{B^2D^2v^2}{R}}$$

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 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 to $x = 2.5D$. 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}.

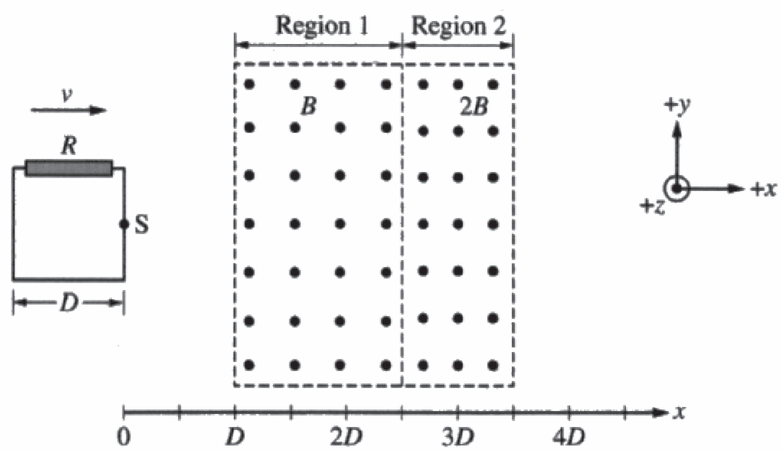


Figure 2

(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.

I proved that power dissipated by the resistor is $\frac{B^2 D^2 v^2}{R}$, so the resistor spending more time in mag. field of strength B decreases the power dissipated compared to spending more time in mag. field of strength 2B, as $P \propto B^2$ and the new configuration w/ same velocity makes the resistor spend more time in mag. field of B.

Question 3

Continue your response to QUESTION 3 on this page.

The original magnetic fields are modified so that the region $D < x < 3.5D$ 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 D and height D. 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-leading corner of the loop.

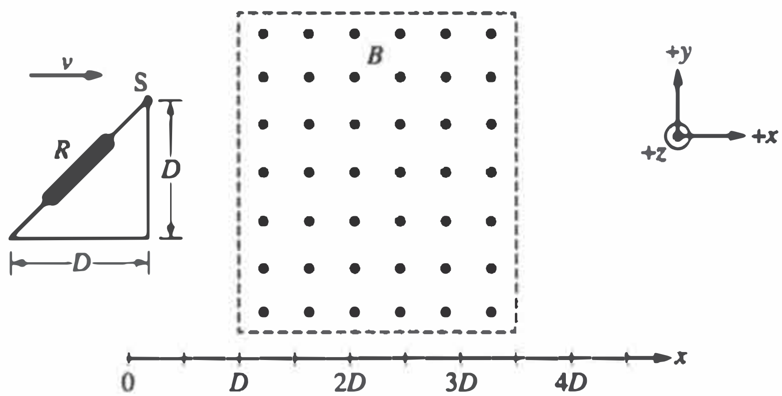
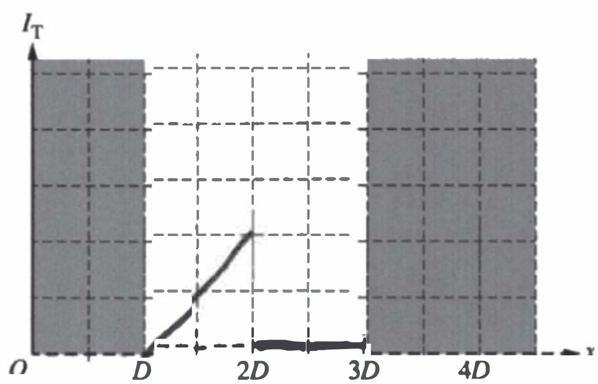


Figure 3

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

$= \frac{BDv}{2}$



Question 3

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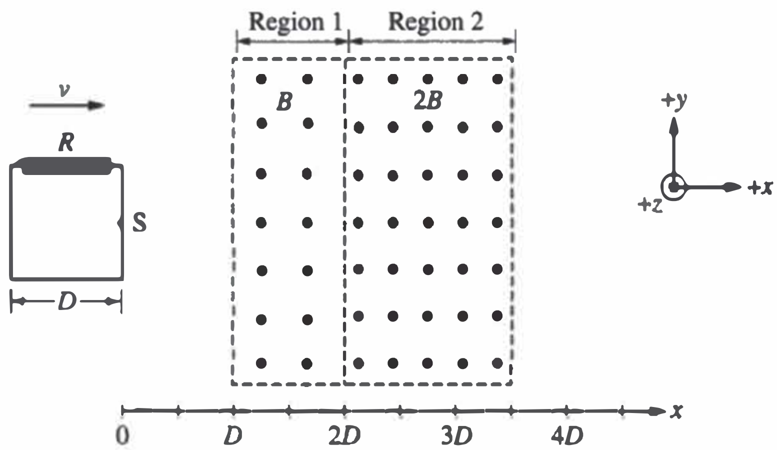

Figure 1

3. 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 then 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 $2B$ 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.

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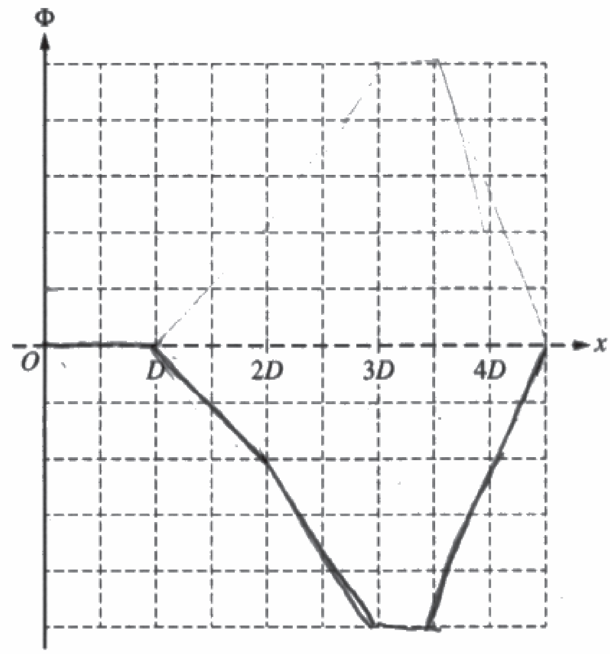
Question 3

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

(a) On the following axes, **sketch** a graph of the magnetic flux Φ through the 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 $+\Phi$.



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

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

V
____ Clockwise ____ Counterclockwise ____ Zero

Briefly **justify** your answer.

Since the magnetic field is into the page the induced magnetic field will have to be out of the page. According to the right hand rule the current will have to be clockwise.

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Question 3

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

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

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

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.

$P = I\Delta V \quad P = I^2R$

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

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 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 to $x = 2.5D$. 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}.

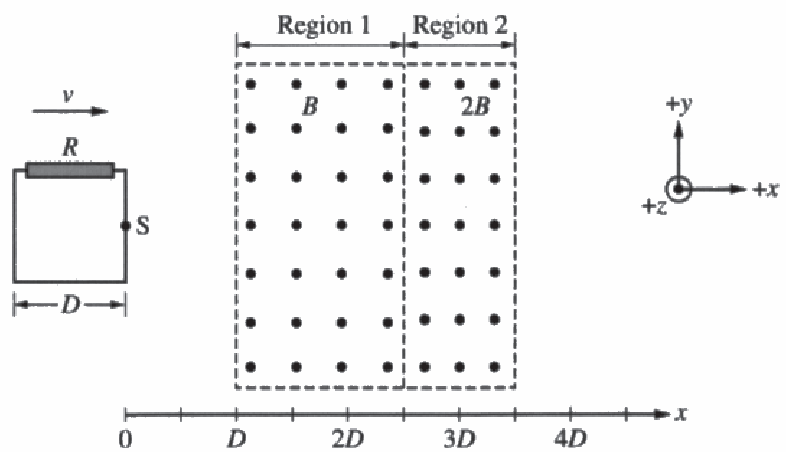


Figure 2

(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.

E original passes through more of region 2 which has a stronger magnetic field, This will cause it to generate a stronger current to oppose the magnetic field. So the energy dissipated by the resistor in E new is greater than E original

Question 3

Continue your response to QUESTION 3 on this page.

The original magnetic fields are modified so that the region $D < x < 3.5D$ 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 D and height D. 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-leading corner of the loop.

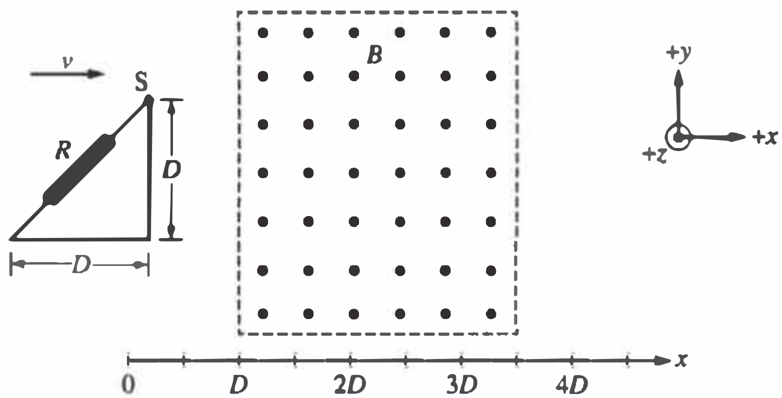
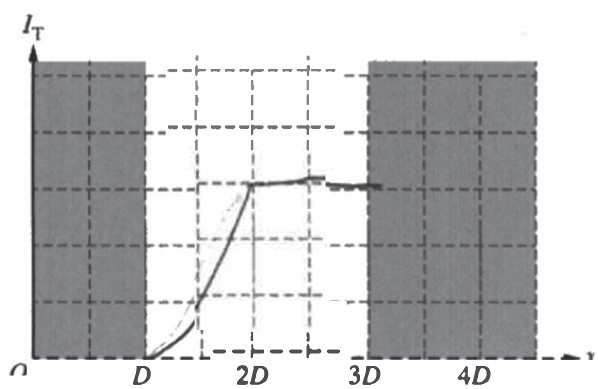


Figure 3

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



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 determine how the absolute value of a magnetic flux through a square loop changes with time as the loop moves with a constant speed into a region that contains magnetic fields of different magnitudes.
- Determine and justify the direction of induced current in the resistor of the square loop due to a changing magnetic flux.
- Derive an expression for induced current in the resistor of the square loop by using Faraday's law and Ohm's law.
- Derive an expression for the power dissipated through the resistor of the square loop due to an induced current.
- Compare and justify the differences in energy dissipation by the resistor of the square loop that is moving through different magnetic fields.
- Graphically represent the induced current in a triangular conducting loop that is entering a magnetic field.

Sample: 3A
Score: 15

Part (a) earned 4 points. The first point was earned for correctly sketching a line that indicates that the magnetic flux is increasing from zero at $x = D$ with a constant slope until $x = 2D$. The second point was earned for correctly sketching a line with a slope from $x = 2D$ to $x = 3D$ that is equal to the slope of the line from $x = D$ to $x = 2D$. The third point was earned for correctly sketching a line that indicates that the magnetic flux has a nonzero constant value from $x = 3D$ to $x = 3.5D$. The fourth point was earned for correctly sketching a line that indicates that the magnetic flux decreases from $x = 3.5D$ to $x = 4.5D$. Part (b) earned 7 points. The first point was earned for correctly selecting a clockwise direction and attempting a relevant justification. The second point was earned for correctly indicating that the magnetic field due to the induced current will be directed in the $-z$-direction. The third point was earned for correctly using Faraday's law in a multistep derivation. The fourth point was earned for correctly indicating $\frac{dA}{dt} = Dv$. The fifth point was earned for correctly using Ohm's law to determine an expression for current I_S that is consistent with the expression determined for the emf. The sixth point was earned for using a correct general expression for power. The seventh point was earned for correctly substituting the expression for current determined in part (b)(ii) into the power expression using only the provided quantities. Part (c) earned 2 points. The first point was earned for correctly selecting $E_{\text{new}} = E_{\text{original}}$ and attempting a relevant justification. The second point was earned for correctly indicating that the change in magnetic flux is the same for both scenarios. Part (d) earned 2 points. The first point was earned for correctly sketching a line that only decreases from $x = D$ to $x = 2D$. The second point was earned for correctly sketching a line that is zero from $x = 2D$ to $x = 3D$.

Question 3 (continued)

Sample: 3B
Score: 9

Part (a) earned 1 point for correctly sketching a line that indicates that the magnetic flux is increasing from zero at $x = D$ with a constant slope until $x = 2D$. The second point was not earned because the response incorrectly sketches a line with a slope from $x = 2D$ to $x = 3D$ that is not equal to the slope of the line from $x = D$ to $x = 2D$. The third point was not earned because the response incorrectly sketches a line that indicates that the magnetic flux is zero from $x = 3D$ to $x = 3.5D$. The fourth point was not earned because the response incorrectly sketches a line that indicates that the magnetic flux decreases to zero from $x = 3.5D$ to $x = 4D$ instead of $x = 4.5D$. Part (b) earned 7 points. The first point was earned for correctly selecting a clockwise direction and attempting a relevant justification. The second point was earned for correctly indicating that the magnetic field due to the induced current will be directed in the $-z$-direction. The third point was earned for correctly using Faraday's law in a multistep derivation. The fourth point was earned for correctly indicating $\frac{dA}{dt} = Dv$. The fifth point was earned for correctly using Ohm's law to determine an expression for current I_S that is consistent with the expression determined for the emf. The sixth point was earned for using a correct general expression for power. The seventh point was earned for correctly substituting the expression for current determined in part (b)(ii) into the power expression using only the provided quantities. Part (c) did not earn any points. The first point was not earned because the response incorrectly selects $E_{new} < E_{original}$. The second point was not earned because the response does not correctly indicate that the change in magnetic flux is the same for both scenarios. Part (d) earned 1 point. The first point was not earned because the response incorrectly sketches a line that that only increases from $x = D$ to $x = 2D$. The second point was earned for correctly sketching a line that is zero from $x = 2D$ to $x = 3D$.

Sample: 3C
Score: 5

Part (a) earned 3 points. The first point was earned for correctly sketching a line that indicates that the absolute value of the magnetic flux is increasing from zero at $x = D$ with a constant slope until $x = 2D$. The second point was not earned because response incorrectly sketches a line with a slope from $x = 2D$ to $x = 3D$ that is not equal to the slope of the line from $x = D$ to $x = 2D$. The third point was earned for correctly sketching a line that indicates that the magnetic flux is a nonzero constant value from $x = 3D$ to $x = 3.5D$. The fourth point was earned for correctly sketching a line that indicates that the absolute value of the magnetic flux decreases from $x = 3.5D$ to $x = 4.5D$. Part (b) earned 2 points. The first point was earned for correctly selecting a clockwise direction and attempting a relevant justification. The second point was earned for correctly indicating that the magnetic field due to the induced current will be directed in the $-z$-direction. The third point was not earned because the response does not use Faraday's law in a multi-step derivation. The fourth point was not earned because response does not correctly indicate that $\frac{dA}{dt} = Dv$. The fifth point was not earned because the response does not correctly use Ohm's law to determine an expression for current I_S that is consistent with the expression determined for the emf. The sixth point was not earned because the response states, but does not use, a correct general expression for power. The seventh point was not earned because the response does not correctly substitute the expression for current that could be determined in part (b)(ii) into a power expression using only the provided quantities. Part (c) did not earn any points. The first point was not earned because the response incorrectly selects $E_{new} > E_{original}$. The second point was not earned because the response does not correctly indicate that the change in magnetic flux is the same for both scenarios. Part (d) did not earn any points. The first point was not earned because the response incorrectly sketches a line that that only increases from $x = D$ to $x = 2D$. The second point was not earned because the response does not sketch a line that is zero from $x = 2D$ to $x = 3D$.