2023

AP® Physics C: Electricity and Magnetism

Sample Student Responses and Scoring Commentary Set 1

Inside:

Free-Response Question 2

☑ Scoring Guidelines

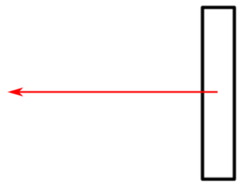
☑ Student Samples

☑ Scoring Commentary

Question 2: Free-Response Question — 15 points

(a)	For drawing an arrow pointing to the left with no extraneous arrows	**1 point**

Example Response



Total for part (a)	**1 point**

(b)(i)	For using Faraday's law to calculate the value of the induced emf	**1 point**

Scoring Note: This point may be earned without the negative sign or a numerical answer.

Example Response

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

For a correct substitution of v for $\frac{dx}{dt}$ **1 point**

Scoring Note: A student can earn points 1 and 2 of part (b)(i) by starting with the expression $\mathcal{E} = BLv$.

Example Response

$$\mathcal{E} = -BL\left(\frac{dx}{dt}\right)$$
$$BL\frac{dx}{dt} = BLv$$

For substituting the correct resistance into an equation for Ohm's law to solve for the current **1 point**

Example Solution

$$\mathcal{E} = -\frac{d\Phi_B}{dt}$$
$$\mathcal{E} = -\frac{d(BLx)}{dt}$$
$$\mathcal{E} = -BL\frac{dx}{dt}$$
$$\mathcal{E} = -BLv$$
$$\mathcal{E} = -(0.50\text{ T})(0.40\text{ m})(2.5\text{ m/s})$$
$$\mathcal{E} = -0.50\text{ V}$$

$$I = \frac{\Delta V}{R}$$
$$I = \frac{|\mathcal{E}|}{R}$$
$$I = \frac{|-0.50\text{ V}|}{0.30\,\Omega} = 1.7\text{ A}$$

(b)(ii)	For substituting the current or an expression for the current obtained from part (b)(i) into an appropriate equation that is related to the magnetic force exerted on the bar	**1 point**

Example Responses

$$\vec{F} = \int I d\vec{\ell} \times \vec{B}$$
$$F = ILB$$
$$F = (1.7 \text{ A})(0.4 \text{ m})(0.5 \text{ T})$$
$$F = 0.33 \text{ N}$$

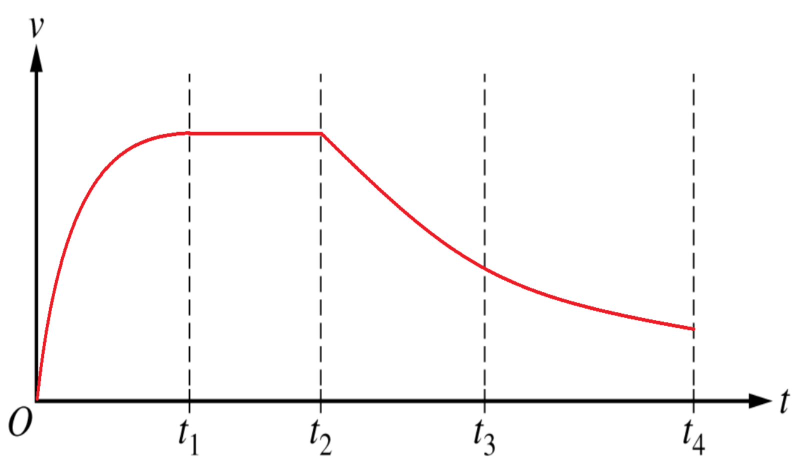
OR

$$\vec{F} = \int I d\vec{\ell} \times \vec{B}$$
$$F = ILB$$
$$F = \left(\frac{BLv}{R}\right)LB$$
$$F = \frac{B^2L^2v}{R}$$
$$F = \frac{(0.5 \text{ T})^2(0.4 \text{ m})^2(2.5 \text{ m/s})}{0.3\,\Omega}$$
$$F = 0.33 \text{ N}$$

Total for part (b) 4 points

(c)	For drawing a curve that starts at the origin, is increasing, and is concave down from $t = 0$ to t_1	**1 point**
	For drawing a horizontal line from t_1 to t_2	**1 point**
	For drawing a curve that is decreasing and concave up from t_2 to t_4	**1 point**
	For drawing a curve that is differentiable at t_3 with a nonzero slope	**1 point**

Example Response



Total Points for part (c) 4 points

(d)(i)	For a correct answer with units ($0.15\,\Omega$)	**1 point**

Scoring Note: This point can be earned without supporting calculations.

Example Response

$$\frac{1}{R_p} = \sum_i \frac{1}{R_i}$$

$$\frac{1}{R_p} = \frac{1}{0.3\,\Omega} + \frac{1}{0.3\,\Omega}$$

$$\frac{1}{R_p} = \frac{2}{0.3\,\Omega}$$

$$R_p = 0.15\,\Omega$$

(d)(ii)	For a statement that correctly describes the inverse relationship between resistance and current (e.g., as resistance decreases current increases)	**1 point**
	For a statement that describes the direct relation between current and force (e.g., as current increases force increases)	**1 point**
	For a statement that describes the direct relation between force and acceleration (e.g., as force increases acceleration increases)	**1 point**

Scoring Note: Full credit can be earned with a justification that is consistent with the resistance calculated in part (d)(i).

Example Response

Since there is less resistance in the new circuit, there will be more current in the new circuit, so a larger force on the bar. Thus, since the force on the bar is larger, the new acceleration is greater than the original acceleration.

Total for part (d) **4 points**

(e)	For correctly indicating **one** of the following, with an attempt at a relevant justification: • Decreasing B • Decreasing L • Increasing m	**1 point**
	For correctly justifying the identified modification that will result in a smaller induced potential difference across the original resistor	**1 point**

Example Responses

The potential difference due to the induced emf *across the original resistor is described by the equation* $\mathcal{E} = -BLv$. *Induced potential difference* $\mathcal{E}$ *is proportional to* B. *Therefore, if the magnitude of the magnetic field is smaller than* $B = 0.5\ \text{T}$ *in the new scenario compared to the original scenario,* $\mathcal{E}$ *would be smaller.*

OR

The potential difference due to the induced emf *across the original resistor is described by the equation* $\mathcal{E} = -BLv$. *The induced potential difference* $\mathcal{E}$ *is proportional to* L, *which represents the distance the conducting rails are separated. Therefore, if* L *is smaller than* $L = 0.4\ \text{m}$, $\mathcal{E}$ *would be smaller.*

OR

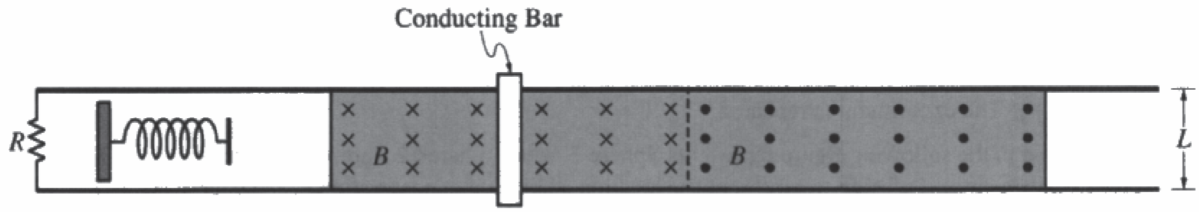
The potential difference due to the induced emf *across the original resistor is described by the equation* $\mathcal{E} = -BLv$. *If the mass of the bar is greater, the velocity entering the magnetic field is less. The induced potential difference* $\mathcal{E}$ *is proportional to* v. *Therefore, a smaller* v *due to a greater mass will induce a smaller* $\mathcal{E}$.

Total for part (e) 2 points

Total for question 2 15 points

Question 2

Begin your response to **QUESTION 2** on this page.



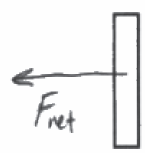
Top View (at time t_B)

2. Two horizontal, parallel, conducting rails are separated by distance $L = 0.40$ m. A resistor of resistance $R = 0.30\ \Omega$ connects the rails. A horizontal ideal spring is located between the rails. The right end of the spring is free to move and the left end is fixed in place. A conducting bar of mass $m = 0.23$ kg is placed on the rails and is in contact with the spring, which is initially compressed. Frictional forces and the resistance of the bar and rails are negligible.

- At time $t = 0$, the bar is released from rest and is pushed to the right by the spring.
- At time t_1, the bar loses contact with the spring and slides to the right.
- At time t_2, the bar enters and travels through a uniform magnetic field of magnitude $B = 0.50$ T that is directed into the page, as shown.
- At time t_3, the bar enters a region where the magnitude of the uniform magnetic field is still $B = 0.50$ T but is directed out of the page.
- At time t_4, the bar enters a region with no magnetic field.

Consider time t_B such that $t_2 < t_B < t_3$.

(a) On the following diagram of the bar, draw an arrow indicating the direction of the net force F_{net} exerted on the bar at time t_B. If the net force is zero, write $F_{net} = 0$.



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Question 2

Continue your response to **QUESTION 2** on this page.

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

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

$A = vtL$

$\frac{dA}{dt} = vL$

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

$= \frac{B\,dA}{dt}$

$= BvL$

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

$I = \frac{BvL}{R}$

$= \frac{(0.5)(2.5)(0.4)}{0.3}$

$= 1.67\text{A}$

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

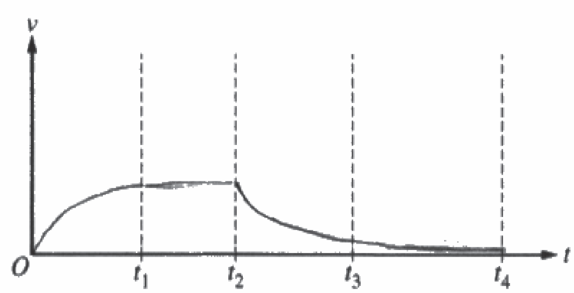
$F_{net} = \int I\,dl \times B$

$= ILB$

$= (1.67)(0.4)(0.5)$

$= 0.333\text{N}$

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



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Question 2

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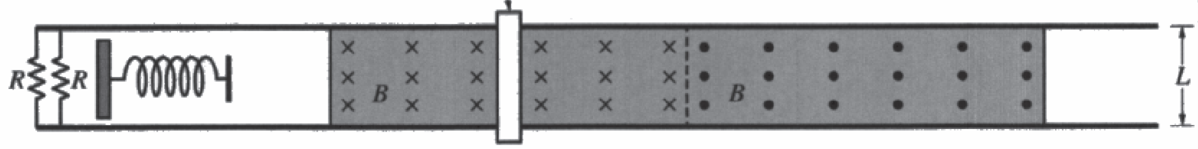
Conducting Bar



Top View (at time t_B)

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

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

$R_{total} = \left(\frac{1}{R}+\frac{1}{R}\right)^{-1} = \frac{1}{\frac{2}{R}} = \frac{R}{2} = \frac{0.3}{2}$ → $\boxed{= 0.15\ \Omega}$

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

Because the total R in the new scenario is lower, & the velocity of the bar is the same as the original, then by (b) part i, the induced current will be larger. by (b) part ii, if the induced current is larger, then the force will be larger.

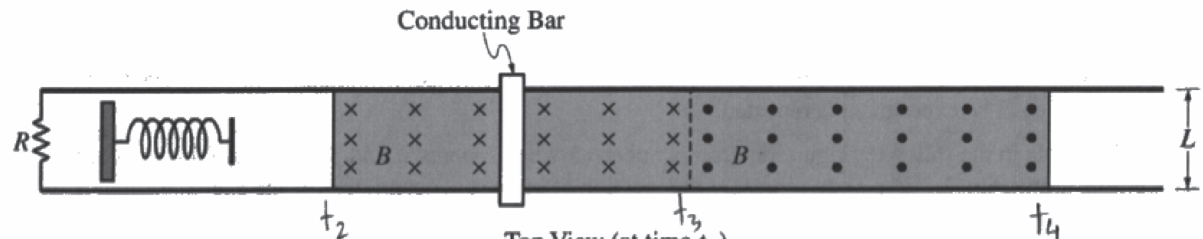
This leads to $a_{new} > a_{original}$

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

If B is smaller, then as $\mathcal{E} = \frac{B\,dA}{dT}$, $\mathcal{E}_{induced}$ will be smaller, meaning the induced potential difference across the original resistor will be smaller.

Question 2

Begin your response to QUESTION 2 on this page.



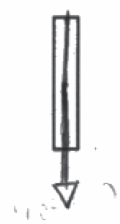
Top View (at time t_B)

2. Two horizontal, parallel, conducting rails are separated by distance $L = 0.40$ m. A resistor of resistance $R = 0.30\ \Omega$ connects the rails. A horizontal ideal spring is located between the rails. The right end of the spring is free to move and the left end is fixed in place. A conducting bar of mass $m = 0.23$ kg is placed on the rails and is in contact with the spring, which is initially compressed. Frictional forces and the resistance of the bar and rails are negligible.

- At time $t = 0$, the bar is released from rest and is pushed to the right by the spring.
- At time t_1, the bar loses contact with the spring and slides to the right.
- At time t_2, the bar enters and travels through a uniform magnetic field of magnitude $B = 0.50$ T that is directed into the page, as shown.
- At time t_3, the bar enters a region where the magnitude of the uniform magnetic field is still $B = 0.50$ T but is directed out of the page.
- At time t_4, the bar enters a region with no magnetic field.

Consider time t_B such that $t_2 < t_B < t_3$.

(a) On the following diagram of the bar, draw an arrow indicating the direction of the net force F_{net} exerted on the bar at time t_B. If the net force is zero, write $F_{net} = 0$.



$F = qv \times B$

Question 2

Continue your response to **QUESTION 2** on this page.

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

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

$$\mathcal{E} = \frac{d\phi_B}{dt} = \frac{dA}{dt} B =$$

$$= (2.5 \text{ m/s})(0.40 \text{ m})(0.50 \text{ T}) =$$

$$= 0.50 \text{ V}$$

$$I = \frac{\mathcal{E}}{R} = \frac{0.50 \text{ V}}{0.30\ \Omega} = \boxed{1.\bar{6} \text{ A}}$$

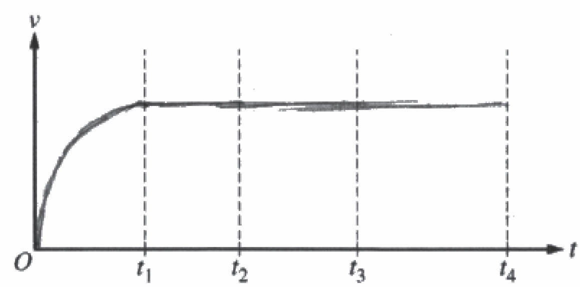
ii. Calculate the magnitude of the net force F_{net} exerted on the bar at time t_B.

$$|F| = qvB$$

$$= q(2.5)(0.50)$$

$$= (1.6)(2.5)(0.50) = \boxed{2 \text{ N}}$$

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



Question 2

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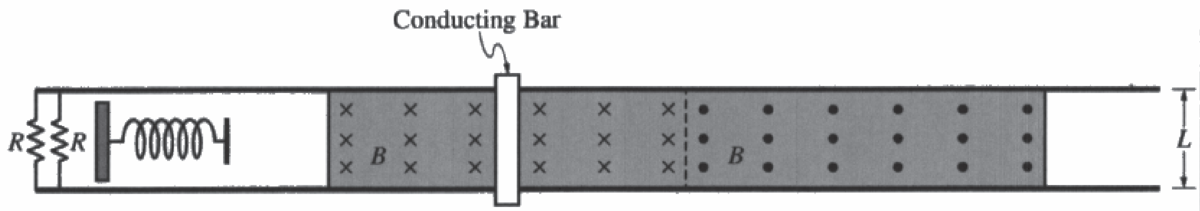


Top View (at time t_B)

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

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

$$\frac{1}{R_{total}} = \frac{1}{R} + \frac{1}{R} = \frac{2}{0.30} = \frac{1}{0.15}$$

$$R_{total} = \boxed{0.15\,\Omega}$$

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

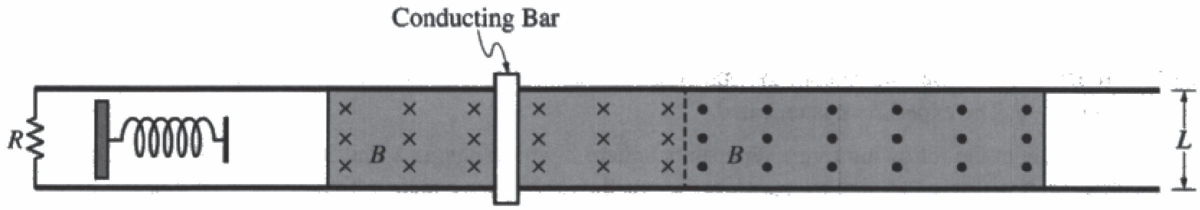
a_{new} will be the same as $a_{original}$ as acceleration does not depend on the resistance immediately after entering the first magnetic field.

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

Decrease B, as the magnitude of induced emf is proportional to the strength of the magnetic field.

Question 2

Begin your response to QUESTION 2 on this page.



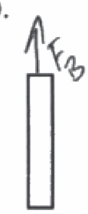
Top View (at time t_B)

2. Two horizontal, parallel, conducting rails are separated by distance $L = 0.40$ m. A resistor of resistance $R = 0.30\ \Omega$ connects the rails. A horizontal ideal spring is located between the rails. The right end of the spring is free to move and the left end is fixed in place. A conducting bar of mass $m = 0.23$ kg is placed on the rails and is in contact with the spring, which is initially compressed. Frictional forces and the resistance of the bar and rails are negligible.

- At time $t = 0$, the bar is released from rest and is pushed to the right by the spring.
- At time t_1, the bar loses contact with the spring and slides to the right.
- At time t_2, the bar enters and travels through a uniform magnetic field of magnitude $B = 0.50$ T that is directed into the page, as shown.
- At time t_3, the bar enters a region where the magnitude of the uniform magnetic field is still $B = 0.50$ T but is directed out of the page.
- At time t_4, the bar enters a region with no magnetic field.

Consider time t_B such that $t_2 < t_B < t_3$.

(a) On the following diagram of the bar, draw an arrow indicating the direction of the net force F_{net} exerted on the bar at time t_B. If the net force is zero, write $F_{net} = 0$.



Question 2

Continue your response to **QUESTION 2** on this page.

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

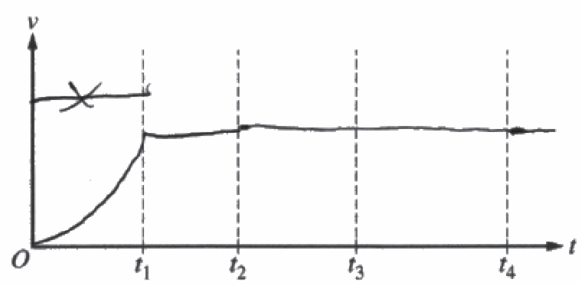
i. Calculate the magnitude of the current in the bar at time t_B.

$B l = \mu_0 I$

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

$F = \int I \, d\vec{l} \cdot \vec{B}$

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



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Question 2

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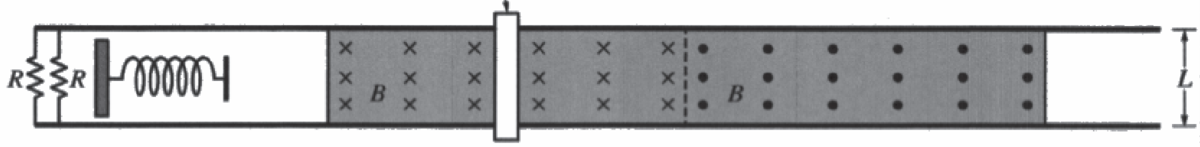

Top View (at time t_B)

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

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

$R_{total} = \left(\frac{1}{0.3} + \frac{1}{0.3}\right)^{-1} = 0.15\ \Omega$

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

equal to, resistance doesn't affect the spring and the force it applies to the bar.

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

decreasing L will decrease the change in area of the magnetic field that ~~goes~~ intersects with the loop thus decreasing the change in magnetic flux and the induced $\mathcal{E}$.

Question 2

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

Overview

The responses were expected to demonstrate the ability to:

- Determine the direction of the induced current and magnetic force on a conducting rod moving through external magnetic fields in a closed loop.
- Solve problems based on the concepts of magnetic induction, including applications of Faraday's law, Lenz's law, and the magnetic force equation.
- Sketch a graph of velocity vs. time for
  - an object affected by a constant (or zero) force;
  - an object affected by a variable force that is dependent on velocity; and
  - an object affected by a variable force that is dependent on position, i.e., the force from an ideal spring.
- Determine equivalent resistance of a network of resistors.
- Apply Ohm's law both numerically and qualitatively to determine and/or analyze current.
- Determine qualitatively the effect of changes in current on magnetic force acting on a current-carrying wire.
- Determine qualitatively the effect of changes in force/mass on magnitude of acceleration.
- Make a claim and justify the functional dependency of B, L, or v on the magnitude of the potential difference across a conducting rod moving through an external uniform magnetic field.

Sample: 2A
Score: 15

Part (a) earned 1 point for drawing the net force in the correct direction. Part (b) earned 4 points. The first point was earned for using Faraday's law to solve for the induced emf. The second point was earned for correctly substituting $\frac{dA}{dt} = L\frac{dx}{dt} = Lv$ so that $\text{emf} = BLv$. The third point was earned for correctly substituting the resistance into Ohm's law to solve for the current in the circuit. The fourth point was earned for substituting the current into an equation that describes the magnetic force exerted on the bar. Part (c) earned 4 points. The first point was earned for drawing a curve starting at the origin that is concave down from $t = 0$ to t_1. The second point was earned for drawing a horizontal line from t_1 to t_2. The third point was earned for drawing a line that is decreasing and concave up from t_2 to t_4. The fourth point was earned for drawing a line that is differentiable and with a nonzero slope at t_3. Part (d) earned 4 points. The first point was earned for correctly determining the total resistance of the circuit with the correct units. The second point was earned for correctly stating the inverse relationship between resistance and current. The third point was earned for correctly stating the direct relationship between current and the magnetic force exerted on the bar. The fourth point was earned for correctly stating the direct relationship between the magnetic force exerted on and the acceleration of the bar. Part (e) earned 2 points. The first point was earned for correctly identifying that a decrease in B will cause a decrease in the potential difference across the original resistor with a relevant justification. The second point was earned for correctly justifying how a decrease in B decreases the potential difference using Faraday's law.

Question 2 (continued)

Sample: 2B
Score: 7

Part (a) earned no points because the response draws the net force in the wrong direction. Part (b) earned 3 points. The first point was earned for using Faraday's law to solve for the induced emf . The second point was earned for correctly equating Faraday's law to BLv . The third point was earned for correctly substituting the resistance into Ohm's law to solve for the current in the bar. The fourth point was not earned because the response does not substitute the current into an appropriate expression for the magnetic force on the bar. Part (c) earned 2 points. The first point was earned for drawing a curve starting at the origin that is concave down from $t = 0$ to t_1 . The second point was earned for drawing a horizontal line from t_1 to t_2 . The third point was not earned because the response draws a line that is not concave up from t_2 to t_4 . The fourth point was not earned because the response draws a line with a slope of zero at t_3 . Part (d) earned 1 point for correctly determining the total resistance of the circuit with the correct units. The second point was not earned because the response does not describe the inverse relationship between resistance and current. The third point was not earned because the response does not relate the current to the magnetic force on the bar. The fourth point was not earned because the response does not relate the magnetic force on the bar to the acceleration of the bar. Part (e) earned 1 point for correctly relating a decrease in B to a decrease in the induced potential difference. The second point was not earned because the response does not specifically address the equation $\mathrm{E} = -BLv$ to justify a response.

Sample: 2C
Score: 4

Part (a) earned no points because the response draws the net force in the wrong direction. Part (b) earned no points. The first point was not earned because the response does not use Faraday's law to solve for the induced emf . The second point was not earned because the response does not substitute $\frac{dx}{dt}$ for the velocity of the bar. The third point was not earned because the response incorrectly uses Ampere's law to solve for the current in the bar. The fourth point was not earned because the response does not substitute the current into an expression for the magnetic force on the bar. Part (c) earned 1 point for drawing a horizontal line from t_1 to t_2 . The second point was not earned because the response draws a curve that is not concave down from $t = 0$ to t_1 . The third point was not earned because the response draws a line that is not concave up from t_2 to t_4 . The fourth point was not earned because the response line is not differentiable at t_3 . Part (d) earned 1 point for determining the total resistance of the circuit with the correct units. The second point was not earned because the response does not describe the inverse relationship between resistance and current. The third point was not earned because the response does not relate the current to the magnetic force on the bar. The fourth point was not earned because the response does not relate the magnetic force on the bar to the acceleration of the bar. Part (e) earned 2 points. The first point was earned for correctly relating a decrease in L to a decrease in the induced potential difference. The second point was earned for correctly describing how a decrease in L decreases the change in magnetic flux and, thus, decreases the induced potential difference.