2023

AP® Physics C: Electricity and Magnetism

Sample Student Responses and Scoring Commentary Set 2

Inside:

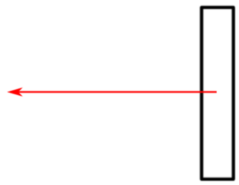
Free-Response Question 2

- ☑ 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

$$\mathcal{E} = -\frac{d\Phi_B}{dt}$$
$$\mathcal{E} = -\frac{d(B_1 dx)}{dt}$$

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 $\mathcal{E} = B_1 dv$.

Example Response

$$\mathcal{E} = -B_1 d\left(\frac{dx}{dt}\right)$$
$$\mathcal{E} = -B_1 dv$$

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

Example Solution

$$\mathcal{E} = -\frac{d\Phi_B}{dt}$$
$$\mathcal{E} = -\frac{d(B_1 dx)}{dt}$$
$$\mathcal{E} = -B_1 d\left(\frac{dx}{dt}\right)$$
$$\mathcal{E} = -B_1 dv$$
$$\mathcal{E} = -(0.40\ \text{T})(0.30\ \text{m})(2.5\ \text{m/s})$$
$$\mathcal{E} = -0.30\ \text{V}$$

$$\Delta V = IR$$
$$I = \frac{\Delta V}{R}$$
$$I = \frac{|\mathcal{E}|}{R}$$
$$I = \frac{|-0.30\ \text{V}|}{0.20\ \Omega} = 1.5\ \text{A}$$

(b)(ii)	For substituting the current or an expression for the current obtained from part (b)(i) into an appropriate equation for calculating the magnetic force	**1 point**

Example Responses

$$\vec{F} = \int I d\vec{\ell} \times \vec{B}$$
$$F = IdB_1$$
$$F = (1.5\text{ A})(0.3\text{ m})(0.4\text{ T})$$
$$F = 0.18\text{ N}$$

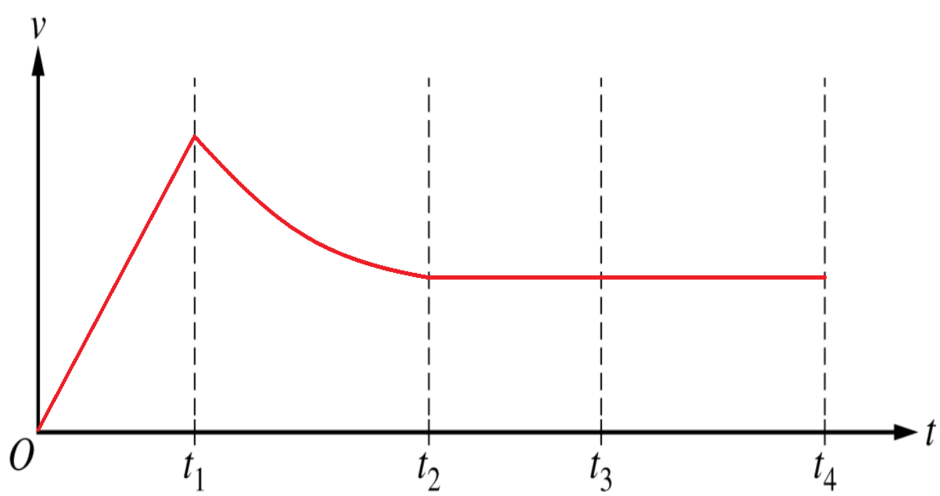
OR

$$\vec{F} = \int I d\vec{\ell} \times \vec{B}$$
$$F = IdB_1$$
$$F = \left(\frac{B_1 dv}{R}\right) dB$$
$$F = \frac{B_1{}^2 d^2 v}{R}$$
$$F = \frac{(0.4\text{ T})^2 (0.3\text{ m})^2 (2.5\text{ m/s})}{0.2\ \Omega}$$
$$F = 0.18\text{ N}$$

Total for part (b) 4 points

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

Example Response



Total Points for part (c) **4 points**

(d)(i)	For a correct answer with units ($0.4\ \Omega$)	**1 point**

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

Example Response

$$R_s = \sum_i R_i$$
$$R_s = (0.2\ \Omega) + (0.2\ \Omega)$$
$$R_s = 0.4\ \Omega$$

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

The new acceleration a_{new} is less than a_{original}. Greater resistance of the bar causes the current to be less than in the original scenario. Less current causes the magnetic force $F = IdB$ on the bar to also be less than the original. By Newton's second law $F = ma$ so less force on a bar of the same mass results in less acceleration.

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

(e)	For correctly indicating **one** of the following, with an attempt at a relevant justification: • Increasing H • Increasing B_1 • Increasing d	**1 point**
	For correctly justifying the identified modification that will result in a larger induced current in the new bar at position x_B	**1 point**

Example Responses

Increasing H will increase the induced current. If the ramp is higher, then the potential energy is greater and this results in greater kinetic energy and greater velocity at the bottom of the ramp. A greater velocity causes a greater rate of change in flux as the bar moves through the field. By Faraday's law the emf *is greater and therefore also the current.*

OR

Increasing B_1 will increase the induced current. If the magnetic field is stronger this increases the flux through the circuit and therefore also the rate of change in the flux. By Faraday's law the emf *is then greater and therefore also the current.*

OR

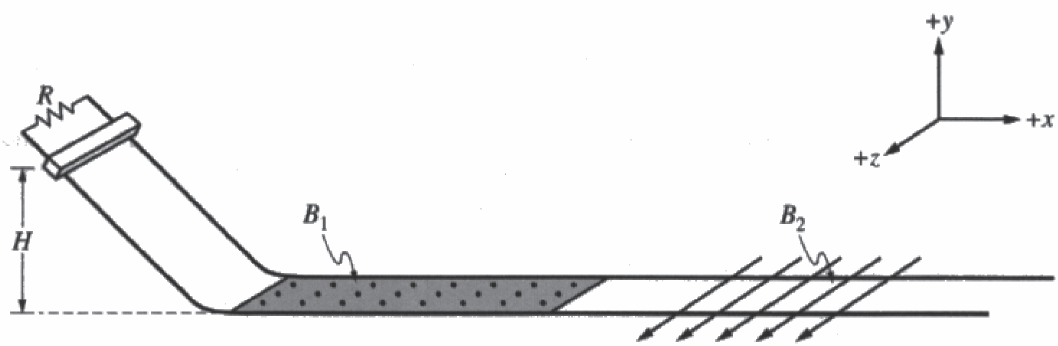
Increasing d will increase the induced current. A larger width results in a greater area encompassed by the circuit. Greater area increases the flux through the circuit and therefore also the rate of change in the flux. By Faraday's law the emf *is then greater and therefore also the current.*

Total for part (e) 2 points

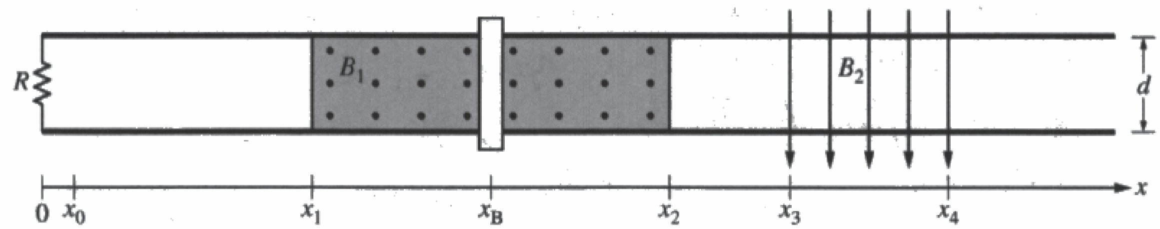
Total for question 2 15 points

Question 2

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



Perspective View (at time $t = 0$)



Top View (at time t_B)

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

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

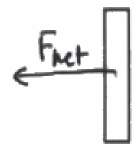
The bar is at position x_B (shown in Top View) at time t_B such that $t_1 < t_B < t_2$.

GO ON TO THE NEXT PAGE.

Question 2

Continue your response to QUESTION 2 on this page.

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



(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.

$\mathcal{E}mf = -N\frac{d\Phi_B}{dt} = -\frac{d\Phi_B}{dt}$ and since B field is constant,

$\mathcal{E}mf = -B\frac{dA}{dt} = -B \cdot d \cdot V$ so

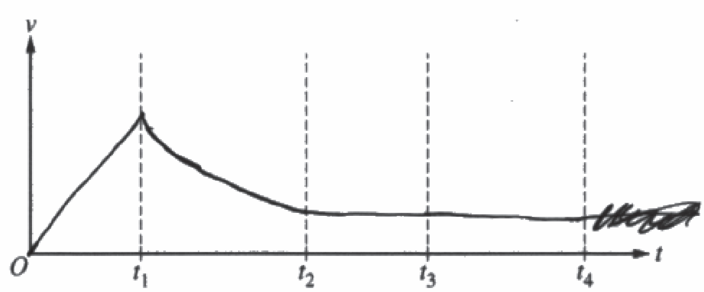
magnitude of current $= \frac{\mathcal{E}mf}{R} = \frac{BdV}{R} = \frac{2.5 \cdot 0.4 \cdot 0.3}{0.2} =$ **1.5 Amps**

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

$|F_{net}| = \int I d\vec{l} \times \vec{B} = I \cdot \int d\vec{l} \times B = IB\int d\vec{l} = IBd$ as $d\vec{l}$ and B are perpendicular. Therefore,

magnitude of net force $= |F_{net}| = 1.5 \cdot 0.4 \cdot 0.3 =$ **0.18 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

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

(d) The original scenario is repeated but with a new bar that has the same mass but with a nonnegligible resistance $R = 0.20\ \Omega$. The new bar is released from rest and smoothly transitions to the horizontal section of the rails and enters the first uniform magnetic field.

i. Determine the total resistance of the closed circuit.

Total resistance = 0.2 + 0.2 = 0.4Ω
as they are in series.

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} is less than $a_{original}$. Since the mass of the two bars are the same, they enter the magnetic field with equal velocity. Also, d and B are still the same. Current = $\frac{Bvd}{R}$, so when R doubles in our new setup current is halved, and Force = BdI so since B and d are constant Force is halved. Mass is equal so a_{new} must be halved, so it is less than $a_{original}$.

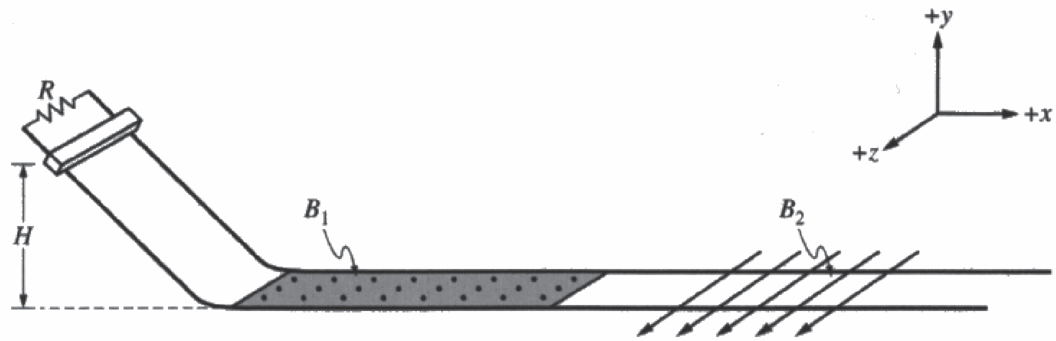
(e) Describe a modification to H, B_1, or d that will result in a larger induced current in the new bar immediately after the bar enters the first uniform magnetic field. Justify your answer.

Current = $\frac{Bvd}{R}$. Therefore, to increase the induced current immediately after the bar enters the first uniform magnetic field, B_1 can be increased as current is proportional directly to B_1, so if B_1 increases current will as well.

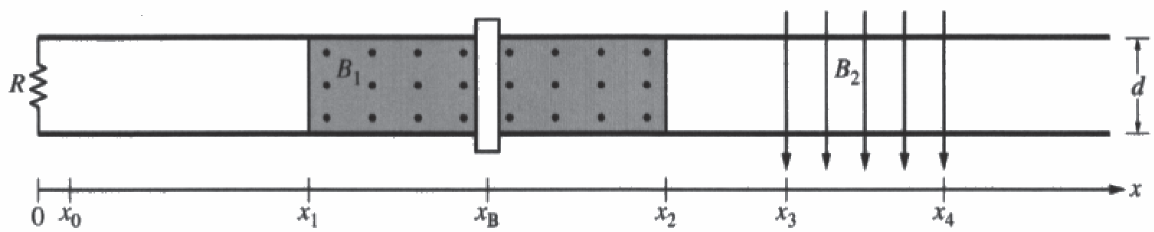
Use a pencil or a pen with black or dark blue ink. Do NOT write your name. Do NOT write outside the box.

Question 2

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



Perspective View (at time $t = 0$)



Top View (at time t_B)

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

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

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

GO ON TO THE NEXT PAGE.

Question 2

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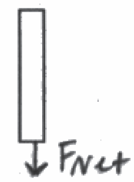
(a) On the following diagram of the bar, as observed from the Top View, draw an arrow indicating the direction of the net force F_{net} exerted on the bar at time t_B. If the net force is zero, write $F_{net} = 0$.



(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.

$V = B\ell\vec{v}$

$V = IR$

$IR = B\ell\vec{v}$

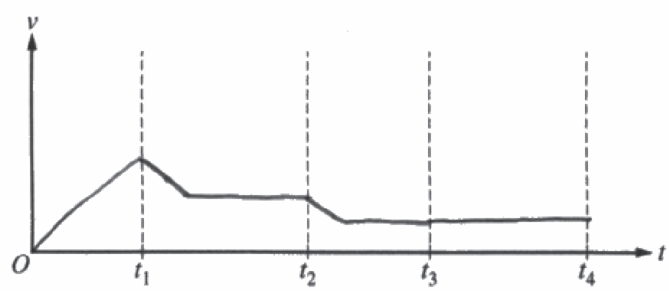
$I = \frac{B\ell\vec{v}}{R} = \frac{0.4 \cdot 0.3 \cdot 2.5}{0.2} = \boxed{1.5A}$

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

$F = BI\ell$

$F = 0.4 \cdot 1.5 \cdot 0.3 = \boxed{0.18N}$

(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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Use a pencil or a pen with black or dark blue ink. Do NOT write your name. Do NOT write outside the box.

Question 2

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(d) The original scenario is repeated but with a new bar that has the same mass but with a nonnegligible resistance $R = 0.20\ \Omega$. The new bar is released from rest and smoothly transitions to the horizontal section of the rails and enters the first uniform magnetic field.

i. Determine the total resistance of the closed circuit.

$R_{eq} = R_1 + R_2 = \boxed{0.40\ \Omega}$

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.

~~greater than~~ because the resisters greater than

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

$V = B\ell\vec{v}$

$V = IR$

$I = \frac{B d \vec{v}}{R}$

Since B and d are in the numerator increasing any of these would directly increase the induced current
As well for increasing the H since the velocity would be greater for if it fell farther thus increasing the current

Question 2

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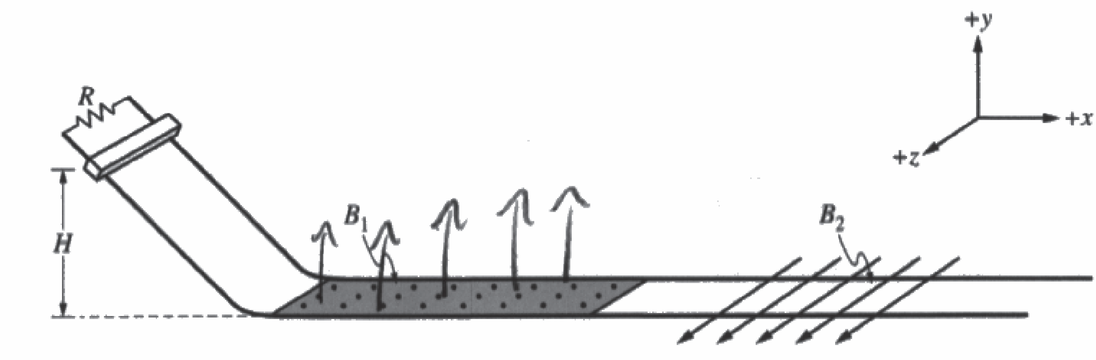
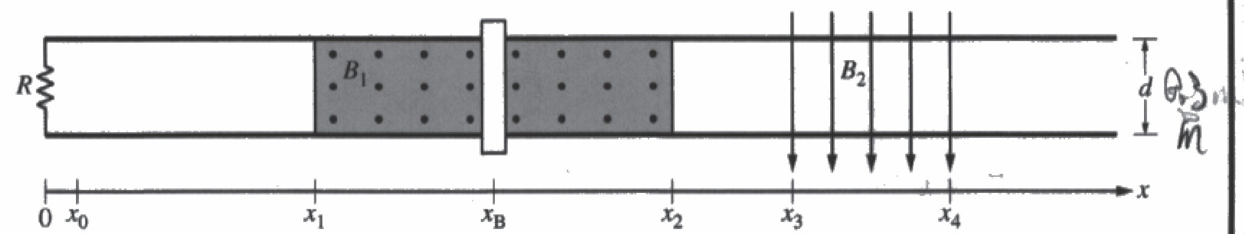


Perspective View (at time $t = 0$)



Top View (at time t_B)

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

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- At time t_2, the bar reaches position x_2 and enters a region with no magnetic field.
- At time t_3, the bar reaches position x_3 and enters a uniform magnetic field of magnitude $B_2 = 0.60$ T that is directed in the $+z$-direction.
- At time t_4, the bar reaches position x_4 and enters a region with no magnetic field.

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

Question 2

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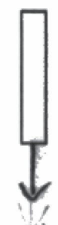


(b) At time t_B, the speed of the bar is $v = 2.5$ m/s.

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

$\vec{F}_M = q\vec{v}\times\vec{B}$

$\vec{F}_M = q\cdot 2.5 m/s\cdot 0.4T$

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

$\oint \vec{B}\cdot d\vec{l} = \mu_0 I$

$\frac{0.4T\cdot 0.3m}{\mu_0} = 95492.96\ A$

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

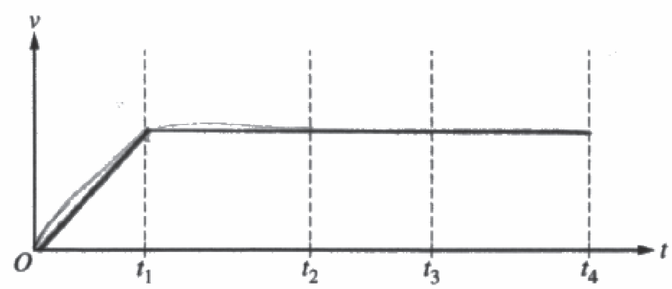
$\Sigma F = ma$

$F_M = q\vec{v}\times\vec{B}$

$F = \int I\,d\vec{l}\times B =$ ~~11459.1552~~

$F_F = 95492.96\cdot 0.3m \times 0.4T = 11459.1552$

(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.



Use a pencil or a pen with black or dark blue ink. Do NOT write your name. Do NOT write outside the box.

Question 2

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

(d) The original scenario is repeated but with a new bar that has the same mass but with a nonnegligible resistance $R = 0.20\ \Omega$. The new bar is released from rest and smoothly transitions to the horizontal section of the rails and enters the first uniform magnetic field.

i. Determine the total resistance of the closed circuit.

$V = IR$

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.

Less than, since the induced current's magnitude is lower than the original

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

Since $\oint B \cdot d\vec{l} = \mu_0 I$, B_1's magnitude can be increased to increase the amount of current induced

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.
- Determine the 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.
- Determine qualitatively the effect of change in height of a ramp on magnitude of speed of an object released down the ramp.

Sample: 2A
Score: 15

Part (a) earned 1 point for correctly indicating the net force on the bar is to the left. Part (b) earned 4 points. The first point was earned for correctly using Faraday's law to calculate the value of the emf. The second point was earned for correctly substituting the speed v for $\frac{dx}{dt}$. The third point was earned for correctly substituting the resistance into an equation for Ohm's law to solve for the current. The fourth point was earned for correctly substituting the current obtained from part (b)(i) into an appropriate equation for calculating the magnetic force exerted on the bar. Part (c) earned 4 points. The first point was earned for correctly indicating a straight line with positive slope that starts at the origin from $t = 0$ to t_1. The second point was earned for indicating a curve that is decreasing and concave up from t_1 to t_2. The third point was earned for correctly indicating a nonzero horizontal line from t_2 to t_3. The fourth point was earned for correctly indicating a nonzero horizontal line from t_3 to t_4. Part (d) earned 4 points. The first point was earned for correctly indicating the total resistance, including units. The second point was earned for correctly indicating that the greater resistance of the circuit results in less current in the new scenario. The third point was earned for correctly indicating that less current through the bar results in less magnetic force in the new scenario. The fourth point was earned for correctly indicating that less force acting on the bar results in less acceleration in the new scenario. Part (e) earned 2 points. The first point was earned for correctly indicating to increase the value of B_1 and attempting a relevant justification. The second point was earned for correctly indicating a valid justification.

Question 2 (continued)

Sample: 2B
Score: 9

Part (a) earned no points because the response incorrectly shows the net force in a direction other than left. Part (b) earned 4 points. The first point was earned for correctly using Faraday's law to calculate the value of the emf . The second point was earned for correctly substituting the speed v for $\frac{dx}{dt}$ (implicit by use of $\text{emf} = BLv$). The third point was earned for correctly substituting the resistance into an equation for Ohm's law to solve for the current. The fourth point was earned for correctly substituting the current obtained from part (b)(i) into an appropriate equation for calculating the magnetic force exerted on the bar. Part (c) earned 2 points. The first point was earned for correctly indicating a straight line with positive slope that starts at the origin from $t = 0$ to t_1. The second point was not earned because, although the response shows speed is decreasing, it is not a curve that is concave up from t_1 to t_2. The third point was not earned because the response does not show a nonzero horizontal line from t_2 to t_3. The fourth point was earned for correctly indicating a nonzero horizontal line from t_3 to t_4. Part (d) earned 1 point for correctly indicating the total resistance, including units. The second point was not earned because the response does not address the effect of resistance of the circuit on the current in the new scenario. The third point was not earned because the response does not address the effect of current through the bar on the magnetic force in the new scenario. The fourth point was not earned because the response does not address the effect of the magnetic force acting on the bar on acceleration in the new scenario. Part (e) earned 2 points. The first point was earned for correctly indicating to increase the value of B_1 and attempting a relevant justification. The second point was earned for correctly indicating a valid justification.

Sample: 2C
Score: 5

Part (a) earned no points because the response incorrectly shows the net force in a direction other than left. Part (b) earned 1 point for correctly substituting the current obtained from part (b)(i) into an appropriate equation for calculating the magnetic force exerted on the bar. The second point was not earned because the response does not use Faraday's law to calculate the induced emf . The third point was not earned because the response does not correctly relate rate of change in flux to the speed of the bar. The fourth point was not earned because the response does not correctly substitute the value of resistance into an equation for Ohm's law to solve for current. Part (c) earned 3 points. The first point was earned for correctly indicating a straight line with positive slope that starts at the origin from $t = 0$ to t_1. The second point was not earned because the response does not indicate a curve that is decreasing and concave up from t_1 to t_2. The third point was earned for correctly indicating a nonzero horizontal line from t_2 to t_3. The fourth point was earned for correctly indicating a nonzero horizontal line from t_3 to t_4. Part (d) earned no points. The first point was not earned because the response has incorrect units for the total resistance. The second point was not earned because the response does not address the effect of resistance of the circuit on the current in the new scenario. The third point was not earned because the response does not address the effect of current through the bar on the magnetic force in the new scenario. The fourth point was not earned because the response does not address the effect of the magnetic force acting on the bar on acceleration in the new scenario. Part (e) earned 1 point for correctly indicating to increase the value of B_1 and attempting a relevant justification. The second point was not earned because the response does not provide a valid justification.