2022

AP® CollegeBoard

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 selecting "Counterclockwise" and an attempt at a relevant justification	**1 point**
For a justification that correctly relates how the changing current in the solenoid changes the flux through the loop with respect to time	**1 point**
For a justification that has a correct relationship between the change in magnetic flux through the loop of wire and how the current in the loop changes to oppose the change in magnetic flux	**1 point**

Example Response

In the end view, the magnetic field due to the solenoid is directed into the page. The current in the solenoid is increasing; thus, the magnetic flux is increasing. According to Lenz's law, because the magnetic flux is increasing and into the page, the current in the loop must create a magnetic field directed out of the page; thus, the current in the loop must be counterclockwise the counter the change in magnetic flux.

Total for part (a) 3 points

(b)

For using an appropriate equation to calculate emf in the loop — **1 point**

Example Response

$$\varepsilon = \left|\frac{d\Phi}{dt}\right| = \frac{d(BA)}{dt} = A\frac{dB}{dt}$$

For correctly substituting the magnetic field for a solenoid into above equation — **1 point**

Example Response

$$\varepsilon = A\frac{d(\mu_0 nI)}{dt} = \mu_0 nA\frac{dI}{dt}$$

For using Ohm's law to calculate the current in the loop — **1 point**

Example Response

$$I_{\text{loop}} = \frac{\varepsilon}{R} = \frac{\mu_0 nA}{R}\frac{dI}{dt}$$

For correctly substituting into the previous equation for the induced current in the loop — **1 point**

Example Response

$$I_{\text{loop}} = \frac{\left(4\pi\times10^{-7}\ \text{T•m/A}\right)\left(\dfrac{500\ \text{turns}}{0.25\ \text{m}}\right)\left((\pi)(0.10\ \text{m})^2\right)}{(3\ \Omega)}(5.0\ \text{A/s}) = 1.3\times10^{-4}\ \text{A}$$

Total for part (b) 4 points

(c)	For using an appropriate expression for the power for a constant current through a resistor **Example Response** $P = I_{\text{loop}}^{2} R$	**1 point**
	For a correct substitution consistent with (b) into a correct expression for electrical power **Example Response** $P = I_{\text{loop}}^{2} R = \left(\dfrac{\mu_0 n A}{R} \dfrac{dI}{dt} \right)^2 R = \left(1.3 \times 10^{-4}\ \text{A}\right)^2 (3.0\ \Omega) = 5.2 \times 10^{-8}\ \text{W}$	**1 point**
	For correctly substituting the power dissipated by the loop of wire into a correct energy equation **Example Response** $P = \dfrac{dE}{dt} = \dfrac{\Delta E}{\Delta t} \therefore \Delta E = P \Delta t$ $\Delta E = \left(5.2 \times 10^{-8} W\right)(2.0\ \text{s}) = 1.0 \times 10^{-7}\ \text{J}$	**1 point**
	Total for part (c)	**3 points**
(d)	For selecting "The plane of the loop is not perpendicular to the axis of the solenoid."	**1 point**
	For correctly justifying the selection **Scoring Note:** A response cannot earn this point if the incorrect selection is chosen.	**1 point**
	Example Response *If the plane of the loop is not perpendicular to the axis of the solenoid it is not perpendicular to the magnetic field. Therefore, the magnetic flux and emf will be less, so the current will be less.*	
	Total for part (d)	**2 points**
(e)	For selecting "$\dfrac{I_2}{I_1} = 2$" with an attempt at a relevant justification **Scoring Note:** The response can earn this point if selecting "$\dfrac{I_2}{I_1} > 2$" and only referencing the increase in flux through the loop in the justification.	**1 point**
	For a statement that indicates that the resistance of the second loop is double the resistance of the original loop	**1 point**
	For a statement that indicates that the new emf is four times greater than the original emf due to the increased flux through the loop resulting from the quadrupled area	**1 point**

Example Response

The magnetic flux quadruples. This is because of the increase in area of the loop, which quadruples the emf. The resistance of the loop doubles because the length of the wire doubles. Therefore, $\frac{I_2}{I_1} = 2$.

$$\varepsilon = \mu_0 n\left(A_{loop}\right) = \mu_0 n\left(\pi r^2\right)\frac{dI}{dt}$$

The radius of the loop doubles. Therefore, the area of the loop quadruples.

$$R = \rho\frac{2\pi r}{A_{wire}}$$

The radius of the loop doubles. Therefore, the resistance of the loop doubles.

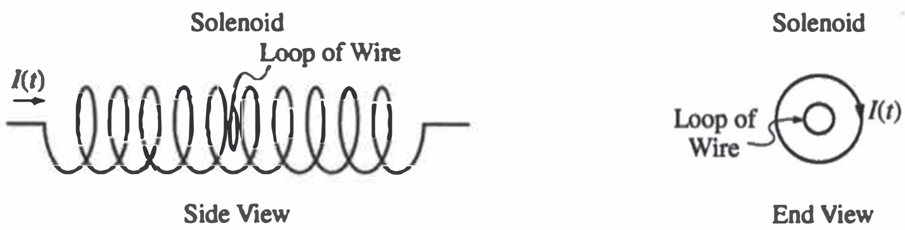
$$\frac{I_2 = \frac{\varepsilon}{R} = \frac{\mu_0 n(4)A}{(2)R}\frac{dI}{dt}}{I_1 = \frac{\varepsilon}{R} = \frac{\mu_0 nA}{R}\frac{dI}{dt}} = 2$$

Total for part (e) 3 points

Total for question 3 15 points

Question 3

Begin your response to QUESTION 3 on this page.



Note: Figures not drawn to scale.

3. A single loop of wire with resistance 3.0 Ω and radius 0.10 m is placed inside a solenoid, with the normal to the loop parallel to the axis of the solenoid. The solenoid has 500 turns, is 0.25 m long, and is connected to a power supply that is not shown. At time $t = 0$, the power supply is turned on, and the current I in the solenoid as a function of t is given by the equation $I(t) = \beta t$, where $\beta = 5.0$ A/s. The direction of the current in the solenoid is clockwise, as shown in the end view.

(a) At time $t = 2.0$ s, is the induced current in the loop, as seen from the end view shown, clockwise, counterclockwise, or zero?

___ Clockwise ✓ Counterclockwise ___ Zero

Justify your answer.

Since $I(t) = \beta t$ is increasing, the flux through the loop is increasing. By Lenz's Law, there will be an induced current to oppose this change in flux. Simple use of the right-hand rule shows that the induced current must be counterclockwise to produce a flux in the opposing direction.

(b) Calculate the current in the loop of wire at time $t = 2.0$ s.

$B(t) = \mu_0 \frac{N}{L} I$

N_{loop} = 1 for the loop

$\Phi = B(t)A$

$= B(t)\pi r^2$

$= \mu_0 \frac{N}{L} I(t) \pi r^2$

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

$\mathcal{E} = -\frac{\mu_0 N \pi r^2}{L}\frac{d}{dt}(\beta t)$

$\mathcal{E} = -\frac{\mu_0 N \pi r^2 \beta}{L}$

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

$I = \frac{-\mu_0 N \pi r^2 \beta}{LR}$

$= \boxed{1.32 \times 10^{-4}\ A}$

GO ON TO THE NEXT PAGE.

Question 3

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

(c) Calculate the total energy dissipated by the loop of wire from time $t = 0$ to time $t = 2.0$ s.

$P = I^2 R$

$E = P\Delta t$

$E = I^2 R \Delta t$

$= \frac{\mu_0^2 N^2 \pi^2 r^4 \beta^2}{L^2 R} \Delta t$

$= \boxed{1.04 \times 10^{-7}\ J}$

(d) A group of students attempts to verify experimentally the calculation of the current from part (b). The current in the inner circular loop at time $t = 2.0$ s is measured to be less than the current calculated in part (b). Which of the following could explain this discrepancy? Select one answer.

___ The experiment did not account for Earth's magnetic field.
✓ The plane of the loop is not perpendicular to the axis of the solenoid.
___ The center of the loop is not on the axis of the solenoid.
___ The resistance of the loop is less than the given value.
___ The radius of the loop is actually larger than 0.10 m.

Justify your answer.

If the plane of the loop is not perpendicular to the solenoid axis, then the flux through the loop is $BA\cos\theta < BA$, since $\theta \neq 0$. ~~Since~~ the flux is actually lower, the induced electromotive force is also lower from Faraday's Law. By Ohm's Law, a lower emf will result in a lower current being experimentally measured.

Question 3

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

(e) The power supply is now turned off. The original loop of wire is then replaced with a second loop made from wire that has the same thickness and is made from the same material as the original loop of wire. The second loop has radius 0.20 m, is placed in the same orientation as the original loop, and fits completely inside the solenoid. The power supply is turned on, and the current I in the solenoid as a function of t is again given by the equation $I(t) = \beta t$, where $\beta = 5.0$ A/s. Which of the following expressions correctly indicates the ratio $\frac{I_2}{I_1}$ where I_1 represents the current induced in the original loop of wire in part (b) and I_2 represents the current induced in the second loop of wire?

___ $\frac{I_2}{I_1} = 1$ ___ $1 < \frac{I_2}{I_1} < 2$ ✓ $\frac{I_2}{I_1} = 2$ ___ $\frac{I_2}{I_1} > 2$

Justify your answer.

From part b, we see that

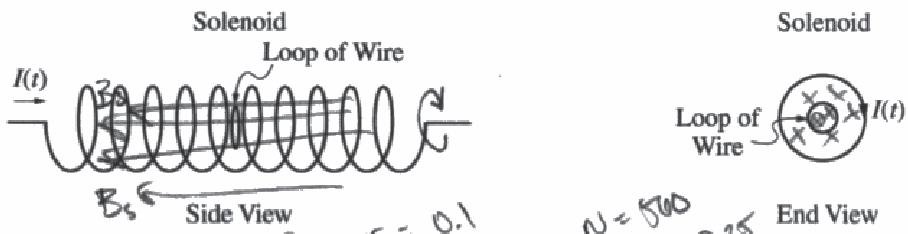
$$I \propto \frac{r^2}{R}$$

If we double the radius of the loop however, we also double its circumference. Since $R = \rho \frac{L}{A}$, we also double its resistance, as L is doubled while ρ, A remain constant.

Thus, I will go up by a factor of $\frac{2^2}{2} = 2$. Therefore $\frac{I_2}{I_1} = 2$.

Question 3

Begin your response to QUESTION 3 on this page.



R = 3Ω   r = 0.1   N = 500   L = 0.25

Note: Figures not drawn to scale.

3. A single loop of wire with resistance 3.0 Ω and radius 0.10 m is placed inside a solenoid, with the normal to the loop parallel to the axis of the solenoid. The solenoid has 500 turns, is 0.25 m long, and is connected to a power supply that is not shown. At time $t = 0$, the power supply is turned on, and the current I in the solenoid as a function of t is given by the equation $I(t) = \beta t$, where $\beta = 5.0$ A/s. The direction of the current in the solenoid is clockwise, as shown in the end view. $I(t) = 5t$

(a) At time $t = 2.0$ s, is the induced current in the loop, as seen from the end view shown, clockwise, counterclockwise, or zero?

___ Clockwise   _X_ Counterclockwise   ___ Zero

Justify your answer.

CCW b/c the ⊗ magnetic field from solenoid will increase over time (look at end view diagram) thus increasing the ⊗ flux. using lenz's law, a current must be induced ccw to induce a magnetic field in the opposite direction and resist this change in flux.

(b) Calculate the current in the loop of wire at time $t = 2.0$ s.

$B = \mu_0 n I = \mu_0 \frac{N}{L} I(t)$

$\Phi = \int B \cdot dA$
$= \int \mu_0 \frac{N}{L} I(t)\, dA$
$= A \mu_0 \frac{N}{L} I(t)$

$\mathcal{E} = IR = \frac{d}{dt}\left(A \mu_0 \frac{N}{L} \beta t\right)$

$I = A \mu_0 \frac{N}{L} \beta = \pi (0.1)^2 \cdot \mu_0 \cdot \frac{500}{0.25} \cdot 5$
$= \boxed{3.95\ E{-4}\ A}$

GO ON TO THE NEXT PAGE.

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

2002148

Q5133/10

Question 3

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

(c) Calculate the total energy dissipated by the loop of wire from time $t = 0$ to time $t = 2.0$ s.

$dP = dI\,\Delta V$

(d) A group of students attempts to verify experimentally the calculation of the current from part (b). The current in the inner circular loop at time $t = 2.0$ s is measured to be less than the current calculated in part (b). Which of the following could explain this discrepancy? Select one answer.

___ The experiment did not account for Earth's magnetic field.
X The plane of the loop is not perpendicular to the axis of the solenoid.
___ The center of the loop is not on the axis of the solenoid.
___ The resistance of the loop is less than the given value.
___ The radius of the loop is actually larger than 0.10 m.

Justify your answer.

If the plane is not ⊥ to the axis, then $\int B \cdot dA$ or the magnetic flux will be less than what we calculated a $B \cdot dA = BA\cos\theta$ and any angle varying from zero will decrease the value of $\cos\theta$.

Question 3

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

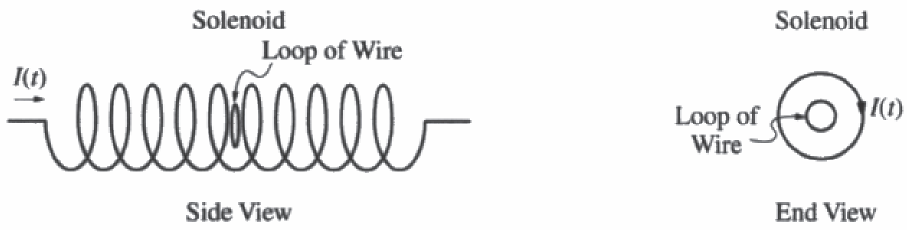
(e) The power supply is now turned off. The original loop of wire is then replaced with a second loop made from wire that has the same thickness and is made from the same material as the original loop of wire. The second loop has radius 0.20 m, is placed in the same orientation as the original loop, and fits completely inside the solenoid. The power supply is turned on, and the current I in the solenoid as a function of t is again given by the equation $I(t) = \beta t$, where $\beta = 5.0$ A/s. Which of the following expressions correctly indicates the ratio $\frac{I_2}{I_1}$ where I_1 represents the current induced in the original loop of wire in part (b) and I_2 represents the current induced in the second loop of wire?

___ $\frac{I_2}{I_1} = 1$ X $1 < \frac{I_2}{I_1} < 2$ ___ $\frac{I_2}{I_1} = 2$ X $\frac{I_2}{I_1} > 2$

Justify your answer.

Question 3

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



Note: Figures not drawn to scale.

3. A single loop of wire with resistance $3.0\ \Omega$ and radius 0.10 m is placed inside a solenoid, with the normal to the loop parallel to the axis of the solenoid. The solenoid has 500 turns, is 0.25 m long, and is connected to a power supply that is not shown. At time $t = 0$, the power supply is turned on, and the current I in the solenoid as a function of t is given by the equation $I(t) = \beta t$, where $\beta = 5.0$ A/s. The direction of the current in the solenoid is clockwise, as shown in the end view.

(a) At time $t = 2.0$ s, is the induced current in the loop, as seen from the end view shown, clockwise, counterclockwise, or zero?

_X_ Clockwise ___ Counterclockwise ___ Zero

Justify your answer.

The current would flow in the same direction as when the current is turned on due to right hand rule. The loops of current cancel each other only leaving the clock wise current.

(b) Calculate the current in the loop of wire at time $t = 2.0$ s.

$B = \mu \cdot I \cdot N$

$n = \frac{\text{Loop}}{\text{Length}}$

$5 =$

$\frac{500}{.25}$

$\frac{500}{.25} \cdot 5 \cdot \pi .1^2$

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

$I = \beta t$

$I = 5(2)$

$I = 10\ \text{A}$

Question 3

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

(c) Calculate the total energy dissipated by the loop of wire from time $t = 0$ to time $t = 2.0$ s.

$E = QV$

$E = Pt$

$P = IV$

$P = V^2/R$

$P = I^2R$

$P = 10^2(3)$

$P = 300$

$E = 300(2)$

$E = 600\text{W}$

(d) A group of students attempts to verify experimentally the calculation of the current from part (b). The current in the inner circular loop at time $t = 2.0$ s is measured to be less than the current calculated in part (b). Which of the following could explain this discrepancy? Select one answer.

___ The experiment did not account for Earth's magnetic field.
___ The plane of the loop is not perpendicular to the axis of the solenoid.
_X_ The center of the loop is not on the axis of the solenoid.
___ The resistance of the loop is less than the given value.
_X_ The radius of the loop is actually larger than 0.10 m.

Justify your answer.

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

$I \propto \frac{1}{R}$

~~more~~ less R = more I

~~A Larger Radius would create a bigger Resistance. $I \propto \frac{1}{R}$ means that a Larger resistance would lead to less I in the Solenoid. Radius effects resistance~~

The center of the loop would have an induced current that would not cancel, and therefore effect the current in the wire, which would cause less current to go through the solenoid

Question 3

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

(e) The power supply is now turned off. The original loop of wire is then replaced with a second loop made from wire that has the same thickness and is made from the same material as the original loop of wire. The second loop has radius 0.20 m, is placed in the same orientation as the original loop, and fits completely inside the solenoid. The power supply is turned on, and the current I in the solenoid as a function of t is again given by the equation $I(t) = \beta t$, where $\beta = 5.0$ A/s. Which of the following expressions correctly indicates the ratio $\frac{I_2}{I_1}$ where I_1 represents the current induced in the original loop of wire in part (b) and I_2 represents the current induced in the second loop of wire?

__ $\frac{I_2}{I_1} = 1$ __ $1 < \frac{I_2}{I_1} < 2$ X $\frac{I_2}{I_1} = 2$ __ $\frac{I_2}{I_1} > 2$

Justify your answer.

I₂ current would be 2 times as big because it is 2 times as large due to the radius being doubled. This would allow for more current to pass through the solenoid.

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:

- Relate an increasing current in a solenoid to an induced current in a loop that is placed inside the solenoid.
- Determine the properties of a current induced by a changing magnetic field using Faraday's law and Lenz's law.
- Apply appropriate right-hand rules to determine directions of magnetic forces and fields.
- Relate the induced current to the energy dissipated within the loop.
- Identify what change could cause the induced current in the loop to be experimentally smaller than anticipated.
- Determine how the induced current would be different with a loop that had both a larger area and larger circumference.

Sample: 3A
Score: 15

Part (a) earned 3 points. The first point was earned because the response correctly identifies that the induced current is in the counterclockwise direction with an attempt at justification. The second point was earned because the response refers to the increasing magnetic flux through the loop caused by the increasing current in the solenoid. The third point was earned because the response indicates that the induced current will oppose the change in flux.
Part (b) earned 4 points. The first point was earned because the response uses Faraday's law to calculate the induced current in the loop. The second point was earned because the response correctly substitutes the magnetic field created by the solenoid into the Faraday's law expression. The third point was earned because the response uses Ohm's law to relate the induced electromotive force to the induced current. The fourth point was earned because the response correctly identifies the value of the induced current as 1.3×10^{-4} A. Part (c) earned 3 points. The first point was earned because the response uses an expression for power through a resistor. The second point was earned because the response correctly substitutes the expression for current from part (b). The third point was earned because the response correctly identifies the amount of energy dissipation for the first two seconds as 1.0×10^{-7} J.
Part (d) earned 2 points. The first point was earned because the response correctly identifies that the plane of the loop not being perpendicular to the axis of the solenoid will correctly account for the discrepancy. The second point was earned because the response connects the decrease in flux caused by the reorientation of the loop to the decrease in induced electromotive force. Part (e) earned 3 points. The first point was earned because the response correctly identifies that the ratio of the currents will be equal to two with an attempt at a justification. The second point was earned because the response mentions that the resistance will increase by a factor of two due to the larger loop radius. The third point was earned because the response refers to an equation in part (b) that correctly relates the electromotive force and the induced current to the area of the loop. This shows that doubling the radius would increase the induced emf by a factor of four.

Question 3 (continued)

Sample: 3B
Score: 8

Part (a) earned 3 points. The first point was earned because the response correctly identifies that the induced current is in the counterclockwise direction with an attempt at justification. The second point was earned because the response refers to the increasing magnetic flux through the loop caused by the increasing current in the solenoid. The third point was earned because the response indicates that the induced current will oppose the change in flux by mentioning that the magnetic field generated by the induced current will be in the opposite direction due to Lenz's law. Part (b) earned 3 points. The first point was earned because the response uses Faraday's law to calculate the induced current in the loop. The second point was earned because the response correctly substitutes the magnetic field created by the solenoid into the Faraday's law expression. The third point was earned because the response uses Ohm's law to relate the induced electromotive force to the induced current. The fourth point was not earned because the response does not correctly substitute the resistance value of 3Ω to solve for the induced current. Part (c) earned 0 points. The first point was not earned because the response does not use an appropriate expression for power in a resistor to find the total energy dissipated during the indicated time. The second point was not earned because the response does not substitute an expression or value for either the current induced or the electromotive force induced in the loop. The third point was not earned because the response does not correctly relate the energy dissipated during the first two seconds to the power through the loop. Part (d) earned 2 points. The first point was earned because the response correctly identifies that the plane of the loop not being perpendicular to the axis of the solenoid will correctly account for the discrepancy. The second point was earned because the response connects the decrease in flux caused by the reorientation of the loop to the decrease in induced electromotive force. Part (e) earned 0 points. The first point was not earned because the response does not indicate the ratio of currents increasing by a factor of two or by a factor greater than two with an attempt at justification. The second point was not earned because the response does not mention the doubling of the effective resistance in the loop due to the increase in loop radius. The third point was not earned because the response does not refer to the increase in induced electromotive force by a factor of four due to the increase in loop radius.

Sample: 3C
Score: 4

Part (a) earned 0 points. The first point was not earned because the response does not correctly identify that the induced current is in the counterclockwise direction with an attempt at justification. The second point was not earned because the response does not refer to the increasing magnetic flux through the loop caused by the increasing current in the solenoid. The third point was not earned because the response does not indicate that the induced current will oppose the change in flux. Part (b) earned 0 points. The first point was not earned because the response does not use Faraday's law to calculate the induced current in the loop. The second point was not earned because the response does not use an expression for the magnetic field generated by the solenoid to find the induced current in the loop. The third point was not earned because the response does not use Ohm's law to relate the induced electromotive force to the induced current. The fourth point was not earned because the response does not substitute values for the loop radius, solenoid turn density, and resistance correctly to measure the induced current in the loop. Part (c) earned 3 points. The first point was earned because the response uses an expression for power through a resistor. The second point was earned because the response correctly substitutes the expression for current from part (b). The third point was earned because the response correctly substitutes the power dissipated into a correct energy equation for the first two seconds. Part (d) earned 0 points. The first point was not earned because the response does not identify that the plane of the loop not being perpendicular to the axis of the solenoid will correctly account for the discrepancy. The second point was not earned because the response does not attempt to justify a correct selection. Part (e) earned 1 point. The first point was earned because the response correctly identifies that the ratio of currents will be equal to two with an attempt at a justification. The second point was not earned because the response does not mention the doubling of the effective resistance in the loop due to the increase in loop radius. The third point was not earned because the response does not refer to the increase in induced electromotive force by a factor of four due to the increase in loop radius.