2022

AP® CollegeBoard

AP® Physics C: Electricity and Magnetism

Sample Student Responses and Scoring Commentary Set 1

Inside:

Free-Response Question 3

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

Question 3: Free-Response Question — 15 points

(a) For selecting "Out of the page" and an attempt at a relevant justification — **1 point**

For a justification that correctly relates how the changing current in the long wire changes the flux through the loop with respect to time — **1 point**

For indicating the induced current will oppose the change in magnetic flux — **1 point**

Example Response

Because the current in the straight wire is decreasing, the magnetic field, which is originally pointing out of the page, is decreasing. Hence, the induced current produces a field that is directed out of the page to compensate for the decreasing flux.

Total for part (a) — 3 points

(b) For using an appropriate integral equation, with a substitution of an expression for magnetic field, to calculate magnetic flux — **1 point**

Example Response

$$\Phi_B = \int \vec{B} \bullet d\vec{A}$$

For writing a correct equation for the magnetic field as a function of distance from the wire — **1 point**

Example Response

$$B = \frac{\mu_0 I}{2\pi r}$$

For substituting the value of $t = 3\text{ s}$ to find the electric current — **1 point**

Example Response

$$I(t) = C - Dt$$
$$I(3\text{ s}) = 10\text{ A} - (2\text{ A/s})(3\text{ s})$$
$$I(3\text{ s}) = 4\text{ A}$$

For integrating B with correct limits and a correct substitution for dA, to determine the total flux through the loop — **1 point**

Example Response

$$\Phi_B = \int_d^{d+W} \frac{\mu_0 IL}{2\pi r} dr$$

$$\Phi_B = \frac{\mu_0 IL}{2\pi} \ln[r]_d^{d+W}$$

$$\Phi_B = \frac{\mu_0 IL}{2\pi} \ln\left[\frac{d+W}{d}\right]$$

$$\Phi_B = \frac{(4\pi \times 10^{-7}\text{ T}\bullet\text{m/A})(4\text{ A})(0.04\text{ m})}{2\pi} \ln\left[\frac{0.03\text{ m}}{0.01\text{ m}}\right] = 3.52 \times 10^{-8}\text{ T}\bullet\text{m}^2$$

Total for part (b) — 4 points

(c) For using Faraday's law to determine the emf across the light bulb **1 point**

Example Response

$$\varepsilon = \left|\frac{d\Phi}{dt}\right|$$

$$\varepsilon = \frac{d}{dt}\left(\frac{\mu_0 (C - Dt) L}{2\pi} \ln\left[\frac{d + W}{d}\right]\right)$$

$$\varepsilon = \left(\frac{\mu_0 DL}{2\pi} \ln\left[\frac{d + W}{d}\right]\right)$$

For using Ohm's law to find the current in the light bulb consistent with the emf determined from the previous point **1 point**

Example Response

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

$$I = \left(\frac{\mu_0 DL}{2\pi R} \ln\left[\frac{d + W}{d}\right]\right)$$

For correct substitutions of the values of $\frac{dI}{dt}$ and R **1 point**

Example Response

$$I = \frac{(4\pi \times 10^{-7}\ \text{T•m/A})(2.0\ \text{A/s})(0.04\ \text{m})}{(2\pi \text{•} 10\Omega)} \ln\left[\frac{0.03\ \text{m}}{0.01\ \text{m}}\right]$$

$$I = 1.8 \times 10^{-9}\ \text{A}$$

Total for part (c) 3 points

(d) For selecting: "The current in the long wire changes at a faster rate than expected." **1 point**

For correctly justifying the selection **1 point**

Scoring Note: A response cannot earn this point if the incorrect selection is chosen.

Example Response

If the current in the wire changes at a faster rate, there will be a greater rate of change of magnetic flux. So the induced emf and current will be higher.

Total for part (d) 2 points

(e)	For selecting "$I_2 < I_1$" with an attempt at a relevant justification	**1 point**
	For indicating the total flux in the loop is less in the new orientation	**1 point**
	For correctly relating the rate of change of the flux to the total flux inside the loop	**1 point**

Example Response

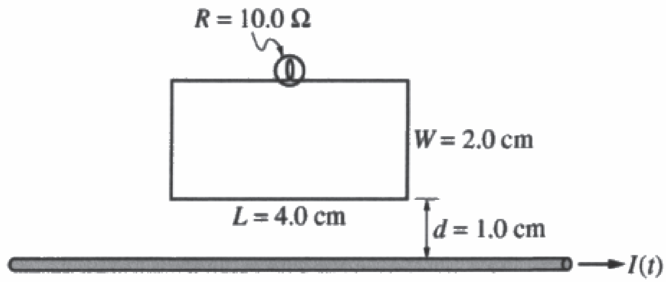
With the new orientation, some parts of the rectangle are further away from the straight wire, which means that the magnetic flux through the rectangle will be less. The rate of change of the flux has the same dependence on distance and will also decrease, resulting in a smaller current.

Total for part (e) 3 points

Total for question 3 15 points

Question 3

Begin your response to QUESTION 3 on this page.



3. A lightbulb of resistance $R = 10.0\ \Omega$ is connected to a rectangular loop of wire of negligible resistance near a very long current-carrying wire. The rectangular loop has a length $L = 4.0$ cm and a width $W = 2.0$ cm and is positioned so one of the longer sides of the loop is a distance $d = 1.0$ cm above and parallel to the long wire, as shown. The current in the long wire is initially flowing to the right and is given by $I(t) = C - Dt$, where $C = 10.0$ A and $D = 2.0$ A/s. At time $t = 5.0$ s, the current in the long wire is instantaneously zero as the current changes direction.

(a) What is the direction, if any, of the magnetic field produced by the induced current in the rectangular loop as the current in the long wire changes direction?

___ Into the page   X Out of the page   ___ No direction, because the field is zero

Justify your answer.

The net flux out of the page is decreasing due to the changing current, so Lenz's law states that the rectangle must induce a B field to counteract that change (so has to be out of the page)

(b) Calculate the magnetic flux through the loop due to only the long wire at time $t = 3.0$ s.

$$\Phi_B = NBA\cos\theta$$

$$= BA$$

$$= \int_{.01m}^{.03m} \frac{\mu_0 I}{4\pi r}(L)\,dr$$

$$= \int_{.01m}^{.03m} \frac{\mu_0(10A - (2A/s)(3sec))}{4\pi r}(.04m)\,dr$$

(using GC) $= \boxed{4.39\times10^{-7}\text{ Webers}}$

Question 3

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

(c) Calculate the current through the lightbulb at time $t = 3.0$ s.

$$\varepsilon = -\frac{dB}{dt} A$$

$$I = \frac{\varepsilon}{R} = -\frac{\frac{dB}{dt} A}{R}$$

$I'(t) = -D$

$$= -\left(\frac{\mu_0 I'(t)}{4\pi r}\right)(LW)$$

$$= -\frac{\mu_0 (-2A/s)}{4\pi (10\Omega)} (.04m)(.02m)$$

$$= \boxed{1.6 \times 10^{-9} A}$$

(d) A group of students attempts to experimentally verify whether the current through the lightbulb is consistent with the current calculation from part (c). The current in the rectangular loop is measured to be greater than the current calculated in part (c). Which of the following could explain this discrepancy? Select one answer.

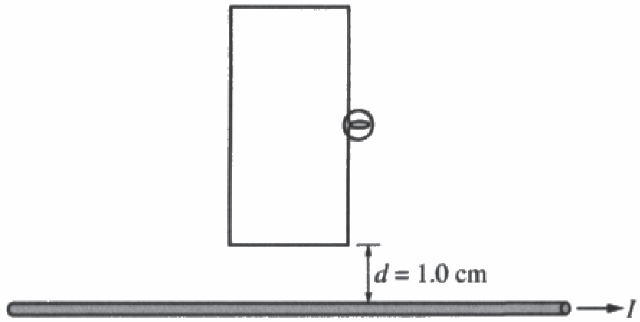
___ The students did not account for Earth's magnetic field.
___ The rectangular loop is tilted and is not in the same plane as the wire.
___ The resistance of the lightbulb is greater than the recorded value.
___ The long side of the rectangular loop is shorter than the recorded value.
_✓_ The current in the long wire changes at a faster rate than expected.

Briefly justify your answer.

If the flux is changing faster than expected, $\frac{d\Phi_B}{dt}$ is greater so a greater emf is induced. That would lead to a greater current than expected

Question 3

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



(e) Later, the same rectangular loop with lightbulb is rotated such that a short side of the loop is 1.0 cm above and parallel to the long current-carrying wire, as shown. The current in the wire is again initially flowing from left to right and given by $I(t) = C - Dt$, where $C = 10.0$ A and $D = 2.0$ A/s. The current through the lightbulb in the loop's new orientation at time $t = 3.0$s is I_2. Which of the following correctly relates the current I_2 to I_1, the current through the lightbulb in part (c)?

X $I_2 < I_1$ ___ $I_2 = I_1$ ___ $I_2 > I_1$

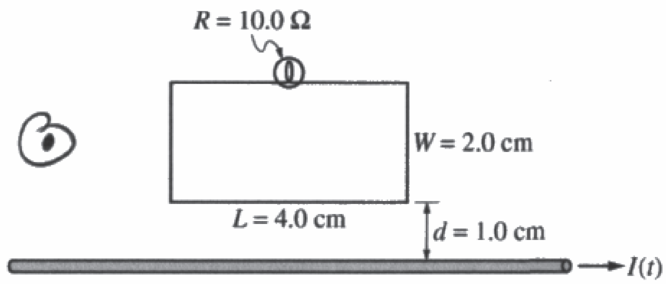
Justify your answer.

The loop will only ever have less flux going through it (b/c some of it is now farther from the wire), but the current decreases at the same rate. So, the amount of flux changing will decrease, but in the same amount of time, so the rate at which it is decreasing is less. So, less emf is induced.

(sorry if that was worded poorly.

Question 3

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



3. A lightbulb of resistance $R = 10.0\ \Omega$ is connected to a rectangular loop of wire of negligible resistance near a very long current-carrying wire. The rectangular loop has a length $L = 4.0$ cm and a width $W = 2.0$ cm and is positioned so one of the longer sides of the loop is a distance $d = 1.0$ cm above and parallel to the long wire, as shown. The current in the long wire is initially flowing to the right and is given by $I(t) = C - Dt$, where $C = 10.0$ A and $D = 2.0$ A/s. At time $t = 5.0$ s, the current in the long wire is instantaneously zero as the current changes direction.

(a) What is the direction, if any, of the magnetic field produced by the induced current in the rectangular loop as the current in the long wire changes direction?

___ Into the page ✓ Out of the page ✓ No direction, because the field is zero

Justify your answer.

The B field produced by current is proportional to current thus is 0 when current is 0.

B from wire $= \frac{\mu_0 I}{2\pi d}$

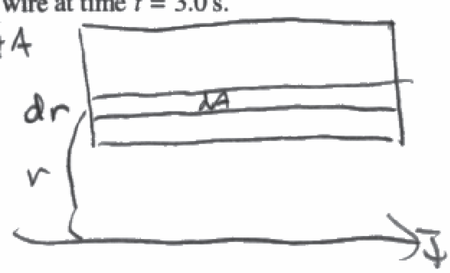
(b) Calculate the magnetic flux through the loop due to only the long wire at time $t = 3.0$ s.

$\Phi_B = \int B \cdot d\vec{A}$ $I(t) = 10 - 2(3) = 4A$

$\Phi = \int_{r=1}^{r=3} \frac{\mu_0 I}{2\pi r} dr \cdot 4$

$dB = \frac{\mu_0 I}{2\pi r}$ $B = \frac{\mu_0 I}{2\pi r}$

$dA = 4dr$



$4 \times \frac{4\pi \times 10^{-7}(4)}{2\pi} \int_{r=1}^{r=3} \frac{1}{r} dr$

$= 3.52 \times 10^{-6}$

Question 3

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

(c) Calculate the current through the lightbulb at time $t = 3.0$ s.

$\mathcal{E} = -\frac{d\Phi_B}{dt}$ $\quad \Phi_B = \frac{4\times 4\pi\times 10^{-7}}{2\pi}\int_1^3 \frac{1}{r}\, dr \times I$

$\frac{d\Phi_B}{dt} = 8.79\times 10^{-7}\frac{dI}{dt}$ $\quad \frac{dI}{dt} = -D = -2$

$\mathcal{E} = 1.76\times 10^{-6}$

$I = \frac{\mathcal{E}}{R} = \frac{1.76\times 10^{-6}\,V}{10\Omega} = 1.76\times 10^{-7}\,A$

(d) A group of students attempts to experimentally verify whether the current through the lightbulb is consistent with the current calculation from part (c). The current in the rectangular loop is measured to be greater than the current calculated in part (c). Which of the following could explain this discrepancy? Select one answer.

✓ The students did not account for Earth's magnetic field.
✓ The rectangular loop is tilted and is not in the same plane as the wire. $dA \downarrow$
✓ ~~The resistance of the lightbulb is greater than the recorded value.~~
✓ The long side of the rectangular loop is shorter than the recorded value.
✓ The current in the long wire changes at a faster rate than expected.

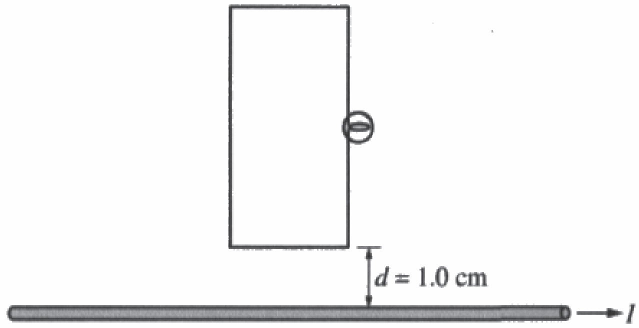
Briefly justify your answer.

~~Earth's magnetic field doesn't matter because its constant so induces no change.~~
~~Tilted rectangular loop decreases B.dA thus decreasing voltage & current~~
~~lower resistance~~

Changing the current faster induces more rate of change in field increasing voltage and thus current.

Question 3

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



(e) Later, the same rectangular loop with lightbulb is rotated such that a short side of the loop is 1.0 cm above and parallel to the long current-carrying wire, as shown. The current in the wire is again initially flowing from left to right and given by $I(t) = C - Dt$, where $C = 10.0$ A and $D = 2.0$ A/s. The current through the lightbulb in the loop's new orientation at time $t = 3.0$s is I_2. Which of the following correctly relates the current I_2 to I_1, the current through the lightbulb in part (c)?

__ $I_2 < I_1$ __ $I_2 = I_1$ ✓ $I_2 > I_1$

Justify your answer.

Question 3

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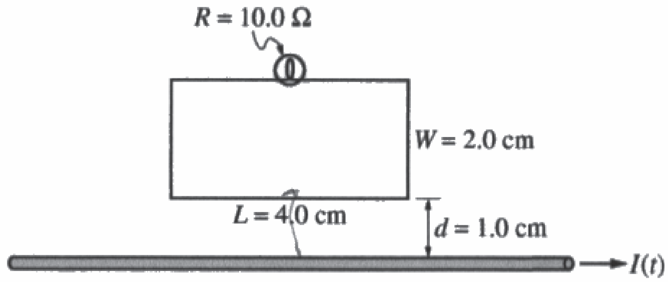


3. A lightbulb of resistance $R = 10.0\ \Omega$ is connected to a rectangular loop of wire of negligible resistance near a very long current-carrying wire. The rectangular loop has a length $L = 4.0$ cm and a width $W = 2.0$ cm and is positioned so one of the longer sides of the loop is a distance $d = 1.0$ cm above and parallel to the long wire, as shown. The current in the long wire is initially flowing to the right and is given by $I(t) = C - Dt$, where $C = 10.0$ A and $D = 2.0$ A/s. At time $t = 5.0$ s, the current in the long wire is instantaneously zero as the current changes direction.

(a) What is the direction, if any, of the magnetic field produced by the induced current in the rectangular loop as the current in the long wire changes direction?

___ Into the page ✓___ Out of the page ___ No direction, because the field is zero

Justify your answer.

Using the Right Hand Rule to determine the direction of the magnetic field as a result of the current's direction, we can see that the B field points out of the page.

(b) Calculate the magnetic flux through the loop due to only the long wire at time $t = 3.0$ s.

$\Phi_B = \int \vec{B} \cdot d\vec{A}$

$\Phi_B = BA$

$\frac{\mu_0 I}{2\pi d} \cdot A$

$\Phi_B = \frac{\mu_0 (C - Dt)}{2\pi d} \cdot (LW)$

$\Phi_B = \frac{\mu_0 (10 - 2(3.0))}{2\pi (0.01)}$ 0.04×0.02

$\Phi_B = 6.4 \times 10^{-8}$

GO ON TO THE NEXT PAGE.

Question 3

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

(c) Calculate the current through the lightbulb at time $t = 3.0$ s.

$$\oint E \cdot dl = \frac{d\Phi_B}{dt}$$

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

$$I = \frac{B(2\pi d)}{\mu_0}$$

(d) A group of students attempts to experimentally verify whether the current through the lightbulb is consistent with the current calculation from part (c). The current in the rectangular loop is measured to be greater than the current calculated in part (c). Which of the following could explain this discrepancy? Select one answer.

___ The students did not account for Earth's magnetic field.
_✓_ The rectangular loop is tilted and is not in the same plane as the wire.
___ The resistance of the lightbulb is greater than the recorded value.
___ The long side of the rectangular loop is shorter than the recorded value.
___ The current in the long wire changes at a faster rate than expected.

Briefly justify your answer.

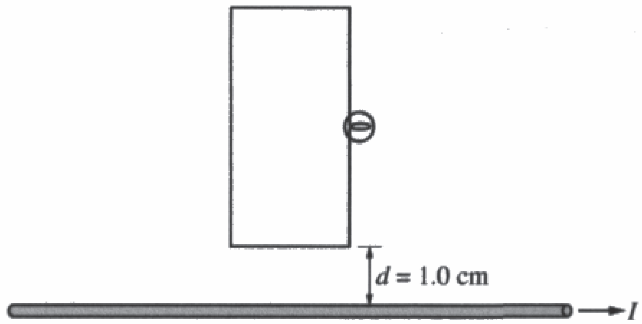
$V = IR$ $F = \int I\, dl \times B$

$F = ILB\sin\theta$

if θ decreases, this means I must increase because the magnetic force stays the same as at 3.0 s, it is not changing and the lightbulb is a fixed distance away from the wire.

Question 3

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



(e) Later, the same rectangular loop with lightbulb is rotated such that a short side of the loop is 1.0 cm above and parallel to the long current-carrying wire, as shown. The current in the wire is again initially flowing from left to right and given by $I(t) = C - Dt$, where $C = 10.0$ A and $D = 2.0$ A/s. The current through the lightbulb in the loop's new orientation at time $t = 3.0$ s is I_2. Which of the following correctly relates the current I_2 to I_1, the current through the lightbulb in part (c)?

✓ $I_2 < I_1$ ✓ $I_2 = I_1$ ___ $I_2 > I_1$

Justify your answer.

~~The shorter side allows for~~

since the d remains the same, the current should be the same

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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:

- Solve problems based on the concepts of magnetic induction, including applications of Faraday's law, Lenz's law, magnetic field, and magnetic flux.
- Determine the properties of a magnetic field produced by a current-carrying wire using Ampere's law or by selection of the correct formula.
- 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.
- Use integral calculus to determine the magnetic flux for a stationary loop of wire located in a variable magnetic field.
- Apply Ohm's law.
- Derive expressions by choosing appropriate fundamental equations, substituting relationships specific to the problem, solving for particular variables, and calculating results with correct numerical values from the prompt.
- Make a claim and justify it using physics principles and laws and analyze the effect of sources of error on experimental outcomes.

Sample: 3A
Score: 14

Part (a) earned 3 points. The first point was earned because the response correctly selects "Out of the page" and attempts a relevant justification. The second point was earned because the response indicates that flux decreases due to the changing current in the long wire. The third point was earned because the response indicates that the induced field opposes the change in flux. Part (b) earned 3 points. The first point was earned because the response has an appropriate integral equation, with substitution for magnetic field, to calculate flux. The second point was not earned because the expression for the magnetic field of a long current-carrying wire is incorrect. The third point was earned because the correct value of time is substituted to determine the current. The fourth point was earned because the limits of integration (from d to $d + W$) are correct and the substitution for the element dA is correct ($dA = Ld\tau$). Part (c) earned 3 points. The first point was earned because the response uses Faraday's law to calculate emf. The second point was earned because Ohm's law is used to find current, and the emf found previously is substituted for voltage in Ohm's law. The third point was earned because the response has a correct substitution for the value of the resistance ($R = 10\,\Omega$) and a correct substitution for the value of $\frac{dI}{dt}$ (= 2 A/s) in order to calculate the induced current. Part (d) earned 2 points. The first point was earned because the response correctly selects "The current in the wire changes at a faster rate than expected." The second point was earned because the response states that the rate of change in flux is greater, which results in a greater induced emf. Part (e) earned 3 points. The first point was earned because the response correctly selects "$I_2 < I_1$" and attempts a relevant justification. The second point was earned because the response states that the flux through the loop is less. The third point was earned because the response states that the rate of change in flux is less.

Question 3 (continued)

Sample: 3B
Score: 9

Part (a) earned 0 points. The first point was not earned because the response does not select "Out of the page" and attempts a relevant justification. The second point was not earned because the response does not indicate that flux decreases due to the changing current in the long wire. The third point was not earned because the response does not indicate that the induced field opposes the change in flux. Part (b) earned 4 points. The first point was earned because the response has an appropriate integral equation, with substitution for magnetic field, to calculate flux. The second point was earned because the response has a correct expression for the magnetic field of a long current-carrying wire. The third point was earned because the correct value of time is substituted to determine the current. The fourth point was earned because the limits of integration (from d to $d + W$) are correct and the substitution for the element dA is correct ($dA = Ld\tau$). Part (c) earned 3 points. The first point was earned because the response uses Faraday's law to calculate emf. The second point was earned because Ohm's law is used to find current, and the emf found previously is substituted for voltage in Ohm's law. The third point was earned because the response has a correct substitution for the value of the resistance and a correct substitution for the value of $\frac{dI}{dt}$ in order to calculate the induced current. Part (d) earned 2 points. The first point was earned because the response correctly selects "The current in the wire changes at a faster rate than expected." The second point was earned because the response states that the rate of change in the magnetic field is greater, which results in a greater induced emf. Part (e) earned 0 points. The first point was not earned because the response does not select "$I_2 < I_1$," and there is no attempt at a relevant justification. The second point was not earned because the response does not state that the flux through the loop is less. The third point was not earned because the response does not state that the rate of change in flux is less.

Sample: 3C
Score: 4

Part (a) earned 1 point. The first point was earned because the response correctly selects "Out of the page" and attempts a relevant justification. The second point was not earned because the response does not indicate that flux decreases due to the changing current in the long wire. The third point was not earned because the response does not indicate that the induced field opposes the change in flux. Part (b) earned 3 points. The first point was earned because the response has an appropriate integral equation, with substitution for magnetic field, to calculate flux. The second point was earned because the response has a correct expression for the magnetic field of a long current-carrying wire. The third point was earned because the correct value of time is substituted to determine the current. The fourth point was not earned because the response shows no limits of integration and incorrect substitution for the element dA. Part (c) earned 0 points. The first point was not earned because the response does not use Faraday's law to calculate emf. The expression is written down but not used. The second point was not earned because Ohm's law is not used to find current. The third point was not earned because the response does not have a correct substitution for the value of the resistance or the value of $\frac{dI}{dt}$ in order to calculate the induced current. Part (d) earned 0 points. The first point was not earned because the response does not correctly select "The current in the wire changes at a faster rate than expected." The second point was not earned because this point cannot be earned if the incorrect selection is chosen. Part (e) earned 0 points. The first point was not earned because the response does not select "$I_2 < I_1$." The second point was not earned because the response does not state that the flux through the loop is less. The third point was not earned because the response does not state that the rate of change in flux is less.