
AP[®] AP Physics C: Electricity & Magnetism

Sample Student Responses and Scoring Commentary

Question #3

DRAFT

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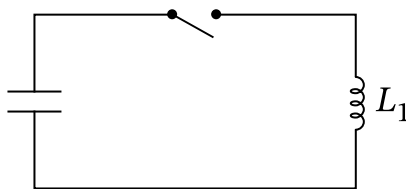
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Question 3

The following information applies to parts A and B.

3. In Experiment 1, students are asked to collect data that can be graphed to determine the inductance L_1 of an inductor. The students have access to multiple charged capacitors, each of a different known capacitance, and a voltmeter that measures potential difference as a function of time. In each trial, the inductor is connected to a charged capacitor and an initially open switch, as shown in Figure 1.

Figure 1

**Part A**

- Indicate** quantities that could be measured by the students that would allow them to determine L_1 using a linear graph.
- Briefly **describe** a method to reduce experimental uncertainty.

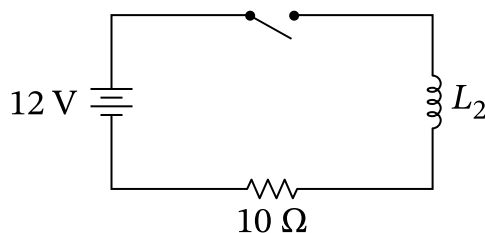
Part B

- Indicate** what quantities the students could graph on the horizontal and vertical axes to create a linear graph that can be used to determine L_1 .
- Briefly **describe** the relationship between L_1 and a feature of the graph from part B (i). Your answer may include an equation that relates L_1 and the chosen feature of the graph.

The following information applies to parts C and D.

In Experiment 2, the students are asked to use a graph to determine the inductance L_2 of a new inductor. The inductor is connected to a 12 V battery, a $10\ \Omega$ resistor, and an initially open switch, as shown in Figure 2.

Figure 2



After the switch is closed, the current I in the circuit is measured at different times and the corresponding rate of change of the current, $\frac{dI}{dt}$, is determined. The collected data are shown in Table 1.

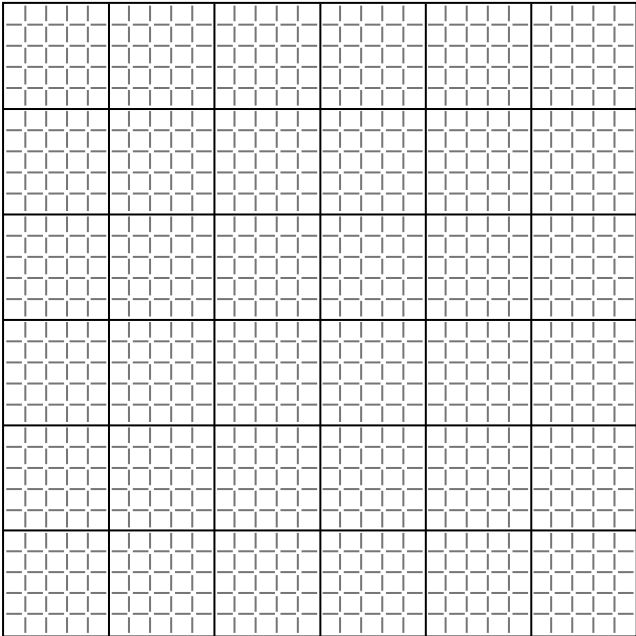
Table 1

I (A)	$\frac{dI}{dt}$ (A/s)
0.40	280
0.50	230
0.75	150
0.90	100
1.00	68

Part C

- i. **Label** the axes of the grid provided with measured or calculated quantities. Include units, as appropriate. The graphed quantities should yield a linear graph that can be used to determine L_2 .
- ii. On the grid provided, create a graph of the quantities indicated in part C (i).
- Clearly **label** each axis with a numerical scale.
 - Plot** the corresponding data points on the grid.
 - Table 2 is provided in your booklet for scratch work and will not be scored.

Quantity (units, if appropriate)



Quantity (units, if appropriate)

- iii. **Draw** a best-fit line for the data plotted in part C (ii).

Part D

Using the best-fit line that you drew in part C (iii), **calculate** an experimental value for L_2 .

Question 3 Experimental Design and Analysis (LAB)**10 points****General Scoring Notes****NR (No Response):** A score of NR is only assigned to responses that are blank.

A	(i)	For indicating that the potential difference across the capacitor or the inductor is measured over time	Point A1
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	(ii)	For indicating a reasonable method of reducing experimental uncertainty Examples of acceptable responses may include the following: • Different capacitors are used in subsequent trials • Multiple trials are completed with the same capacitor	Point A2
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Example Response

Measure the potential difference across the capacitor as a function of time after the switch is closed for long enough to measure the period of oscillation. Repeat the procedure with different capacitors in subsequent trials.

B	(i)	For indicating appropriate quantities that can be graphed to determine L_1 , consistent with the response in part A (i), such as:	Point B1
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- T as a function of $\sqrt{C}$
- T^2 as a function of C
- Angular frequency ω as a function of $\sqrt{\frac{1}{C}}$

Scoring Note: Responses that include the reciprocals of the preceding examples, in addition to other equivalent graphs, also earn this point.

	(ii)	For correctly relating an appropriate feature of the graph to L_1	Point B2
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Example Response

Graph T as a function of $2\pi\sqrt{C}$. The slope of the best-fit line is equal to $\sqrt{L_1}$.

C (i) For indicating appropriate quantities that can be graphed to determine L_2 , for example: **Point C1**

- $\Delta V_{\text{Battery}} - IR$ as a function of $\frac{dI}{dt}$
- ΔV_L as a function of $\frac{dI}{dt}$

Scoring Note: This point may be earned

- If the vertical and horizontal variables are reversed
- For other equivalent graphs

(ii) For labeling **both** axes (including units where appropriate) with a linear scale **Point C2**

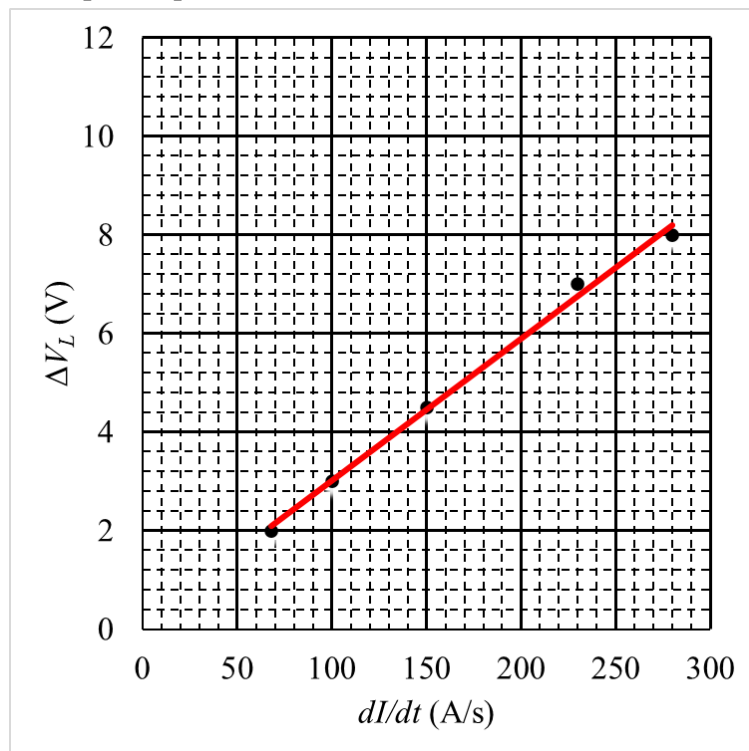
Point C3

For correctly plotting data points consistent with **one** of the following:

- The quantities indicated in part C (i)
- The quantities provided in the table

(iii) For drawing a line or curve that approximates the trend of the plotted data **Point C4**

Example Response



D	For correctly relating the slope of the best-fit line of the graph to L_2	Point D1
	For a value of L_2 that is within a range of 0.026 H to 0.032 H	Point D2

Example Response

Determine the Potential Difference Across the Inductor.

$$\Delta V_{\text{Battery}} - \Delta V_R - \Delta V_L = 0$$

$$\Delta V_L = \Delta V_{\text{Battery}} - \Delta V_R$$

$$\Delta V_L = \Delta V_{\text{Battery}} - IR$$

Determine the Inductance of the Inductor.

$$|\Delta V_L| = L \frac{dI}{dt}$$

$$\text{slope} = L = \frac{\Delta(|\Delta V_L|)}{\Delta\left(\frac{dI}{dt}\right)}$$

$$\frac{\Delta(|\Delta V_L|)}{\Delta\left(\frac{dI}{dt}\right)} = \frac{(7.7 \text{ V}) - (5.3 \text{ V})}{(260 \text{ A/s}) - (180 \text{ A/s})}$$

$$\therefore L_2 = 0.03 \text{ H}$$

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

Question 3

PART A

- i 1) Measure the potential difference across a capacitor ΔV at time $t=0$
- x ii 2) Measure the potential difference at a later time $t=T$ when the potential difference is the same as before
- ii 3) Repeat steps 1 & 2 with multiple capacitors and for each capacitor average T over many trials to reduce uncertainty (record corresponding capacitance C)

PART B

- i Students could plot values of $\frac{T^2}{4\pi^2}$ on the vertical axis and values of C on the horizontal axis,
- x and the slope of the line of best fit will
- ii be the experimental value of the inductance L .

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

Question 3

PART C

Quantity (units, if appropriate)

12-10I

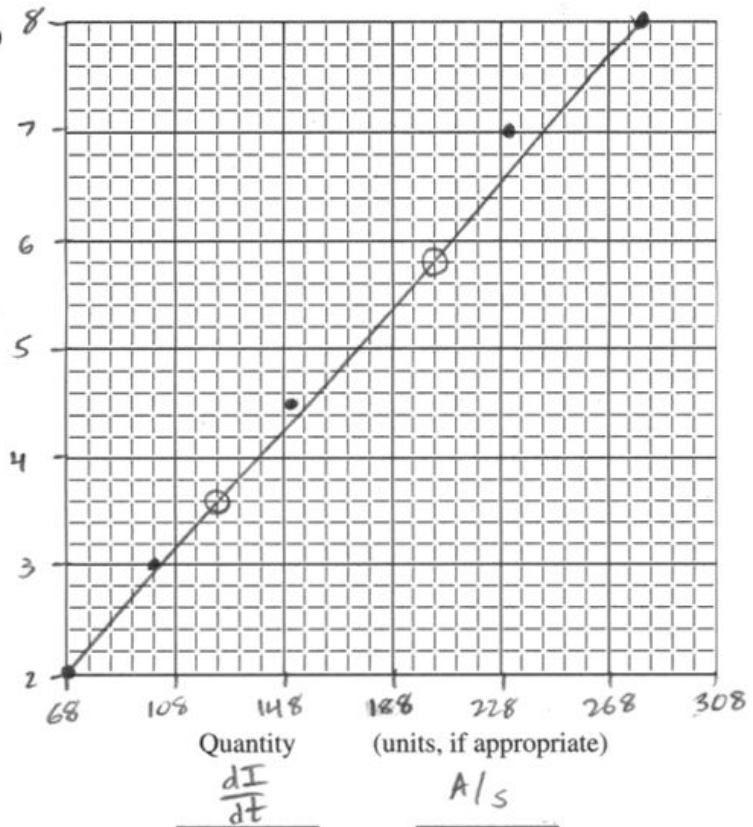
V

0.2 I

Table 2

Anything you write in Table 2 will not be scored.

12-10I	$\frac{dI}{dt}$
8	280
7	230
4.5	150
3	100
2	68



PART D

$$\sum \Delta V = 0$$

$$\mathcal{E} - IR = L \frac{dI}{dt} = 0$$

$$10 - 12I = L \frac{dI}{dt}$$

$$L = \frac{10 - 12I}{\left(\frac{dI}{dt}\right)} = \text{slope} \approx \frac{5.8 - 3.6}{204 - 124} = 0.0275 \text{ H}$$

Go to Question 4 when you're done with this question.

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

Question 3

PART A

i. Period of Voltage
Capacitance of capacitors

ii. Repeat trials with different capacitances

PART B

i. horizontal C

vertical $\left(\frac{T}{2\pi}\right)^2$

ii. the slope of the graph
equals L.

$$\begin{aligned} \omega &= \frac{1}{\sqrt{LC}} \\ T &= \frac{2\pi}{\omega} \\ T &= \frac{2\pi}{\frac{1}{\sqrt{LC}}} \\ T &= 2\pi\sqrt{LC} \end{aligned}$$

$$\left(\frac{T}{2\pi}\right)^2 = LC$$

$$y = mx$$

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

Question 3

PART C

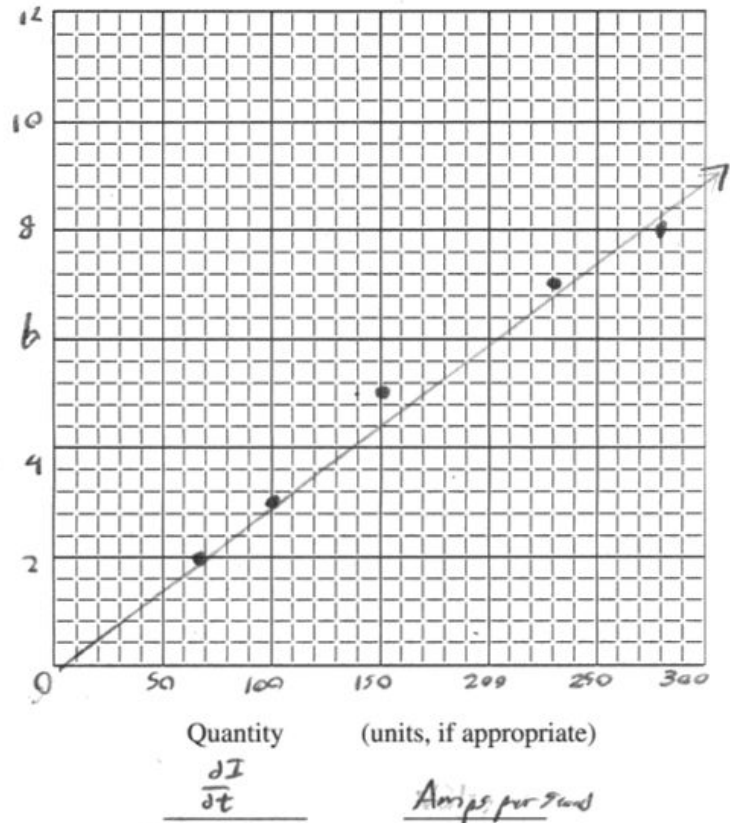
Quantity (units, if appropriate)

$12 - 10(I)$ Volts

Table 2

Anything you write in Table 2 will not be scored.

$\frac{dI}{dt}$	$V - IR$
280	8
230	7
150	4.5
100	3
60	2



PART D

$$L = \frac{\Delta y}{\Delta x}$$

$$L = \frac{280 - 60}{8 - 2}$$

$$L = \frac{212}{6}$$

$$L = 35.333 \text{ H}$$

Go to Question 4 when you're done with this question.

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

Question 3

PART A

- i. measure the capacitance of each capacitor C in μF
- measure the period of the voltage vs time graphs T from the voltmeter (sec)
- ii. For each capacitor run the trial multiple times to get 3 or more graphs and when finding T use at least 3 peaks to get a nice average

PART B

i. y-axis = T^2 (sec²) x-axis = C (μF)

- ii. the graph is a $T^2 = 4\pi^2 LC$ so therefore the slope of the graph is $4\pi^2 L$, find L by solving algebraically with the known constants

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

Question 3

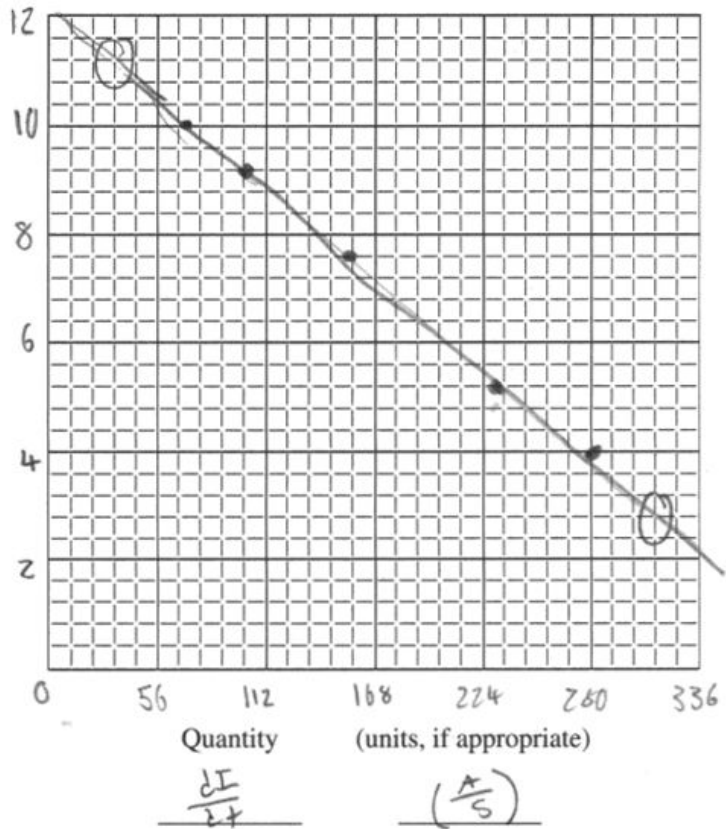
PART C

Quantity (units, if appropriate)
 V_R V
 voltage across
 resistor ($I R$)

Table 2

Anything you write in Table 2
 will not be scored.

$V_R (V)$	
4	
5	
7.5	
9	
10	



PART D

$$\frac{y_2 - y_1}{x_2 - x_1} = \frac{2.8 - 11.2}{314 - 336} = -0.022457 = 4\pi^2 L$$

$$\frac{-0.022457}{4\pi^2} = L$$

$$7.58 \times 10^{-4} = L$$

Go to Question 4 when you're done with this question.

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

Question 3

PART A

- i. They could measure the Voltage across the capacitor and the time intervals for it to return back to its max
- ii. Run the trials 3 times per capacitor and average the values for the time (period)

→ We are doing this because it says they can measure voltage as a function of time.

PART B

$$2\pi\sqrt{LC} = T$$

$$4\pi^2 LC = T^2$$

- i. On the y axis, the period for it to reach back to its max voltage, squared could be graphed and on the x axis, the capacitance of the capacitor
- ii. The slope can be use to find L of the inductor

$$i. \begin{aligned} 2\pi\sqrt{LC} &= T \\ 4\pi^2 LC &= T^2 \rightarrow mx + b = y \\ (4\pi^2 L)C &= T^2 \end{aligned}$$

$$\text{slope} = 4\pi^2 L$$

$$\boxed{\frac{\text{slope}}{4\pi^2} = L}$$

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

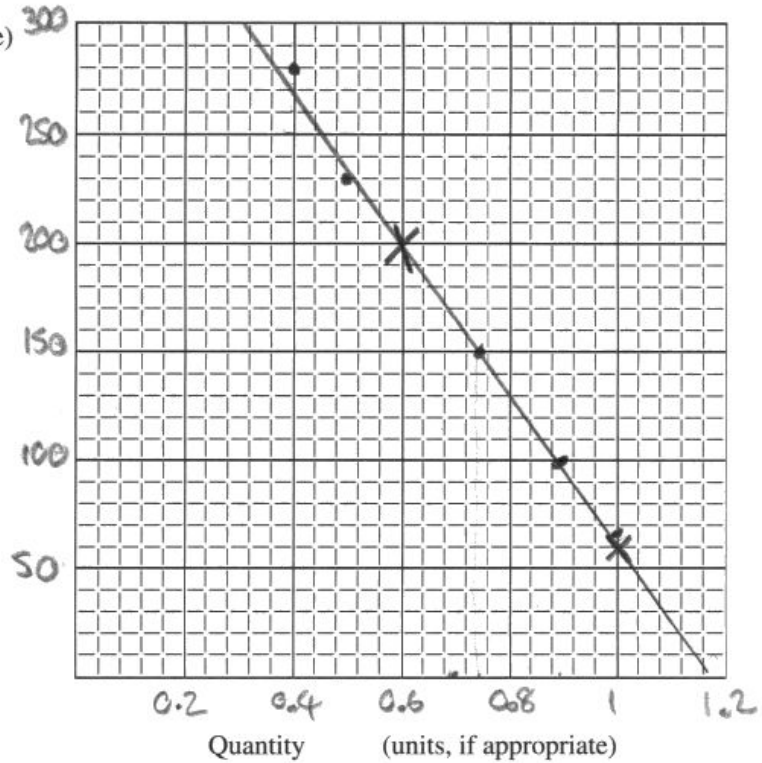
Question 3

PART C

Quantity (units, if appropriate)
Rate of
current $\left(\frac{dI}{dt}\right)$ $\frac{A}{s}$

Table 2

Anything you write in Table 2
 will not be scored.



PART D

$$\mathcal{E} = -L \frac{dI}{dt}$$

$$IR = -L \frac{dI}{dt}$$

$$I = -\frac{L}{R} \frac{dI}{dt}$$

$$\text{slope} = \frac{200 - 60}{0.6 - 1} = -139.6$$

$$-139.6 = -\frac{L}{R}$$

$$139.6 R = L \rightarrow 1396 \frac{V \cdot s}{A}$$

$\frac{A}{s}$

Go to Question 4 when you're done with this question.

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

Question 3

PART A The students should measure the voltage across each capacitor and the inductor using the voltmeter. To decrease experimental uncertainty do this multiple times with different capacitors to get the voltage.

Measure initial voltage of capacitor and note when it drops to 37% of initial ΔV . Count the seconds.

PART B

Using the known capacitance, find the charge using $C = \frac{Q}{\Delta V}$. Then find the current with $\frac{dQ}{dt}$. Then, using the known voltage, subtract the voltage of

The time constant of a LC circuit is $\frac{L}{C}$ and this is how long it takes for the capacitor to lose 63% ΔV . ~~The~~ $\tau = \frac{L}{C}$ use this with the known capacitance to find $LC = L$ and L is LC_1

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

Question 3

PART C

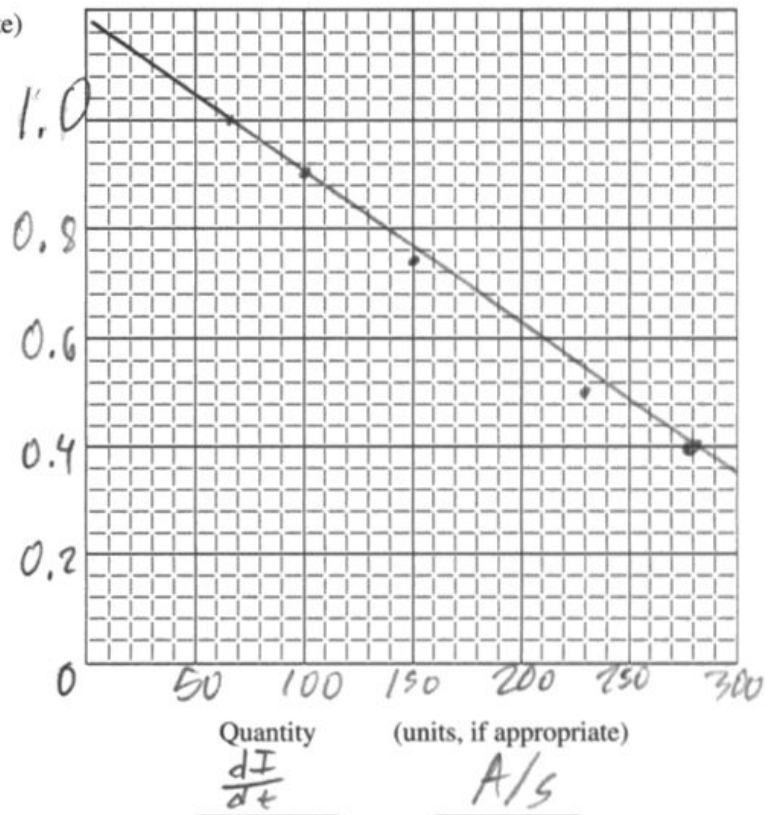
Quantity (units, if appropriate)

Current

A

Table 2

Anything you write in Table 2
will not be scored.



PART D

The slope is $\frac{A}{A/s} = -5$. Plug this
into $1 - e^{-\frac{t}{\tau}}$ to find τ which
is equal to $RL = 10L$
 $L = -0.00514958 L$

Go to Question 4 when you're done with this question.

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

Question 3

PART A

- i Area of inductor
Number of loops
Length of inductor
Current
- ii - run experiment multiple times
- make sure capacitors do not lose charge in between runs

PART B

y-axis = current

x-axis = time

$$\mathcal{E} = -L \frac{dI}{dt}$$

If current over time is found then it will be easier to find L when $\mathcal{E}$ is found or given.

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

Question 3

PART C

Quantity (units, if appropriate)

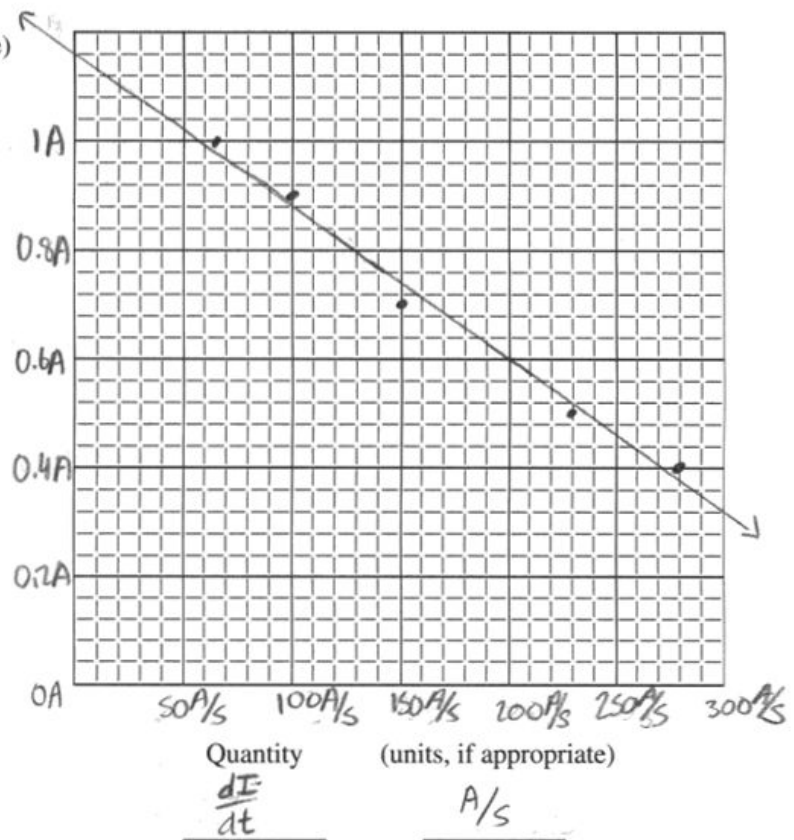
Current

A

Table 2

Anything you write in Table 2
will not be scored.

It's Linear!!	☺



PART D

$$\mathcal{E} = -L \frac{dI}{dt}$$

$$\mathcal{E} = 12V \quad 12V = -L(280)$$

$$L = -.043$$

Go to Question 4 when you're done with this question.

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

Question 3

PART A

$$\mathcal{E} = -L \frac{dI}{dt}$$

the students could measure the current running through the circuit

to reduce uncertainty, the students could

PART B

$$i) Q = CV \quad U_C = \frac{1}{2} C V^2 \quad U_L = \frac{1}{2} L I^2 \quad U_C - U_L = \Delta V$$

$$\frac{1}{2} C V^2 - \frac{1}{2} L I^2 = \Delta V \quad L = \frac{C \Delta V^2 - 2 \Delta V}{I^2}$$

on the vertical axis, the student could graph the difference between the squares of potential difference and potential difference

on the horizontal axis, the student could graph ii) the square of the current.

$$L = \frac{C \Delta V^2 - 2 \Delta V}{I^2}$$

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

Question 3

PART C

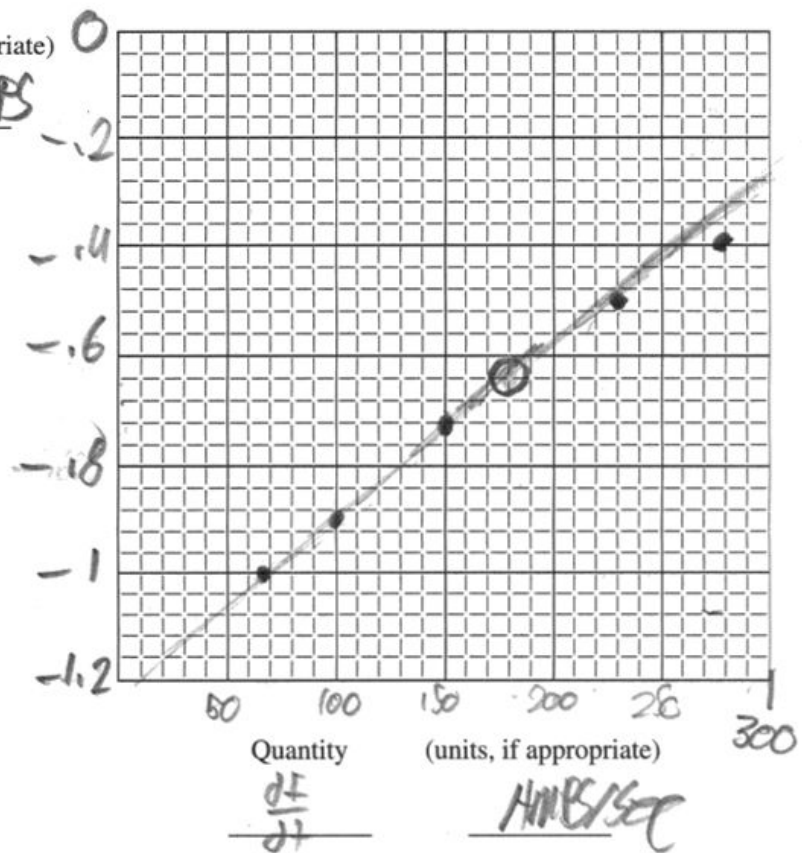
Quantity (units, if appropriate)

$-I$

AmBS

Table 2
Anything you write in Table 2
will not be scored.

$-I$	$\frac{dI}{dt}$
-0.4	280
-0.5	230
-0.75	150
-0.9	100
-1	68



PART D

$$L = \frac{-I}{\frac{dI}{dt}} (R)$$

$$L = \left(\frac{-0.36}{144} \right) (10)$$

$$= .025 \text{ H}$$

Go to Question 4 when you're done with this question.

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

Question 3

PART A

- i. $\mathcal{E}$ = emf and t = time
- ii. To reduce experimental uncertainty it is crucial to re-do the trials multiple times and obtain data to a high number of sig figs. Multiple trials ensures the data is not skewed and high sig figs ensure zero rounding errors.

PART B

- i. $\mathcal{E}$ = emf on the vertical axis and t = time on the horizontal axis.
- ii. $\mathcal{E} = -L \frac{dI}{dt}$ therefore by graphing $\mathcal{E}$ and time the slope of the graph gives us the negative L value. Taking the derivative or calculating the slope of $\mathcal{E}$ in terms of t gives us the value of L .

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

Question 3

PART C

$$R = 10 \Omega \quad V = 12V$$

Quantity (units, if appropriate)

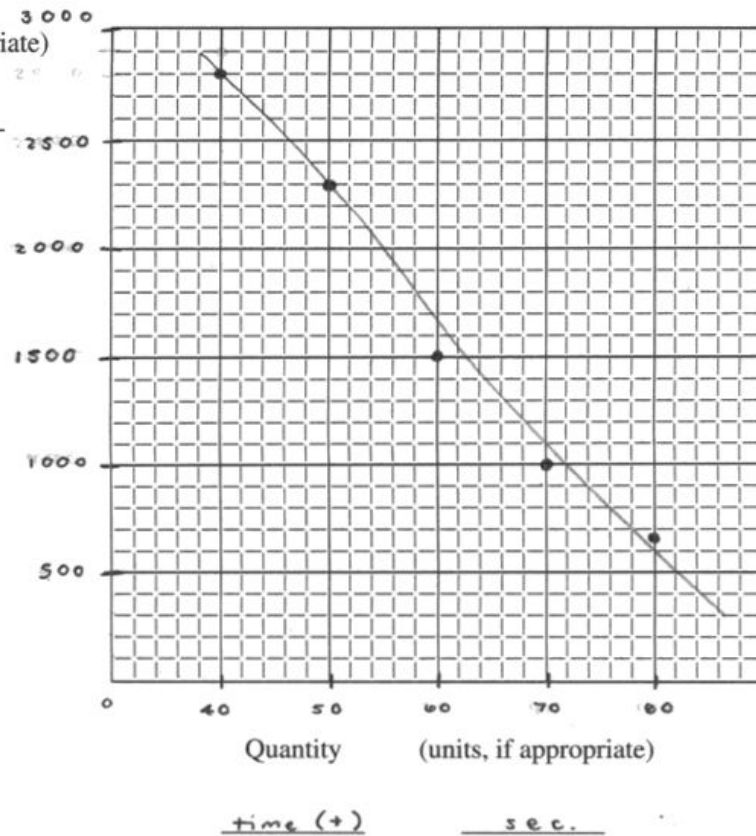
emf ($\mathcal{E}$)

V

Table 2

Anything you write in Table 2
will not be scored.

time	$\mathcal{E}$
	2800
	2300
	1500
	1000
	600



PART D

$$\text{slope} = \frac{500}{10} = 50 \text{ V/s} \quad \text{therefore } L = 50 \text{ T}$$

Using the derivative of the current and plugging it into $V = IR$ to find the electric potential yields a graph in which the slope itself is the value of inductance.

Go to Question 4 when you're done with this question.

Question 3

Sample Identifier: PCEM Sample 3A

Score: 10

- Point A1 was earned. The response indicates that the potential difference across the capacitor is measured over time.
- Point A2 was earned. The response indicates that multiple trials could be used to reduce uncertainty. Multiple capacitors are used, and each capacitor is used multiple times. Either of those claims by itself is sufficient to earn this point.
- Point B1 was earned. The response indicates quantities that can be graphed to produce a linear graph. Correct responses make use of the equation $\omega^2 = 1/(LC)$. In this case, the substitution $\omega = 2\pi/T$ is used as well.
- Point B2 was earned. The response correctly indicates that the slope of the graph would be equal to L_1 .
- Point C1 was earned. The response indicates that the potential difference across the inductor (which is equal to the actual quantity graphed: battery voltage - IR) and the derivative of the current with respect to time are quantities to graph that will produce a linear graph.
- Point C2 was earned. The response includes appropriate labels with units on the axes, and the graph has a linear scale.
- Point C3 was earned. The response correctly plots points that are consistent with the quantities labeled in part C (i).
- Point C4 was earned. The response includes a best-fit line that approximates the trend of the plotted data.
- Point D1 was earned. The response correctly indicates that the slope of the best-fit line is equal to L_2 .
- Point D2 was earned. The calculated value of inductance is between 0.026 H and 0.032 H.

Sample Identifier: PCEM Sample 3B

Score: 9

- Point A1 was earned. The response does indicate that the potential difference was measured over a time interval.
- Point A2 was earned. The response indicates that multiple trials could be used to reduce uncertainty.
- Point B1 was earned. The response indicates that $(T/2\pi)^2$ and C can be graphed to produce a linear graph.
- Point B2 was earned. The response indicates that the slope of the graph would be equal to L_1 .
- Point C1 was earned. The response indicates that the potential difference across the inductor and the derivative of the current with respect to time are quantities that will produce a linear graph.
- Point C2 was earned. The response includes appropriate labels with units on the axes, and the graph has a linear scale.
- Point C3 was earned. The points plotted on the graph are consistent with the quantities labeled in part C (i).
- Point C4 was earned. The response includes a best fit line that approximates the trend of the plotted data.

- Point D1 was earned. The response indicates that the slope of the best-fit line is equal to L_2 .
- Point D2 was not earned. The value for L_2 is not between 0.026 H and 0.032 H.

Sample Identifier: PCEM Sample 3C**Score: 8**

- Point A1 was earned. The response indicates that the period T of a voltage vs time graph was measured.
- Point A2 was earned. The response indicates that multiple trials could be used to reduce uncertainty.
- Point B1 was earned. The response does indicate two variables that produce a linear graph, period squared and capacitance.
- Point B2 was earned. The response correctly states how the slope is related to L_1 .
- Point C1 was earned. The response indicates that the potential difference across the resistor and the derivative of the current with respect to time are quantities that produce a linear graph.
- Point C2 was earned. The response includes appropriate labels with units on the axes, and the graph has a linear scale.
- Point C3 was earned. The points plotted on the graph are consistent with the quantities labeled in part C (i).
- Point C4 was earned. The response includes a best fit line that approximates the trend of the plotted data.
- Point D1 was not earned. The response does not indicate a correct relationship between the slope of the best-fit line and L_2 .
- Point D2 was not earned. The response does not have a value for L_2 that is between 0.026 H and 0.032 H.

Sample Identifier: PCEM Sample 3D**Score: 8**

- Point A1 was earned. The response indicates that the potential difference is measured over time.
- Point A2 was earned. The response indicates that multiple trials could be used to reduce uncertainty.
- Point B1 was earned. The response does indicate two variables that produce a linear graph.
- Point B2 was earned. The response correctly indicates how slope relates to L_1 .
- Point C1 was earned. The response indicates that the derivative of the current with respect to time and current are quantities that produce a linear graph.
- Point C2 was earned. The response includes appropriate labels with units on the axes, and the graph has a linear scale.
- Point C3 was earned. The points plotted on the graph are consistent with the quantities labeled in part C (i).
- Point C4 was earned. The response includes a best fit line that approximates the trend of the plotted data.

- Point D1 was not earned. The response does not indicate a correct relationship between the slope of the best-fit line and L_2 .
- Point D2 was not earned. The response does not have a value for L_2 that is between 0.026 H and 0.032 H.

Sample Identifier: PCEM Sample 3E**Score: 6**

- Point A1 was earned. The response indicates that the potential difference across the device is measured over time.
- Point A2 was earned. The response indicates that multiple capacitors could be used to reduce uncertainty.
- Point B1 was not earned. The response does not indicate two variables that produce a linear graph.
- Point B2 was not earned. The response does not indicate the use of a feature of the graph to find L_1 .
- Point C1 was earned. The response indicates that the current and the derivative of the current with respect to time are quantities that produce a linear graph.
- Point C2 was earned. The response includes appropriate labels with units on the axes, and the graph has a linear scale.
- Point C3 was earned. The points plotted on the graph are consistent with the quantities labeled in part C (i).
- Point C4 was earned. The response includes a best-fit line that approximates the trend of the plotted data.
- Point D1 was not earned. The response does not indicate how the slope of the best-fit line is related to L_2 .
- Point D2 was not earned. The response does not have a value for L_2 that is between 0.026 H and 0.032 H.

Sample Identifier: PCEM Sample 3F**Score: 5**

- Point A1 was not earned. The response does not indicate that the potential difference over time was measured.
- Point A2 was earned. The response indicates that multiple trials could be used to reduce uncertainty.
- Point B1 was not earned. The response does not indicate two variables that will produce a linear graph.
- Point B2 was not earned. The response does not indicate the use of a feature of the graph to find L_1 .
- Point C1 was earned. The response indicates that the current and the derivative of the current with respect to time are the quantities to graph to produce a linear graph.
- Point C2 was earned. The response includes appropriate labels with units on the axes, and the graph has a linear scale.
- Point C3 was earned. The points plotted on the graph are consistent with the quantities labeled in part C (i).

- Point C4 was earned. The response includes a best-fit line that approximates the trend of the plotted data.
- Point D1 was not earned. The response does not indicate how the slope of the best-fit line is related to L_2 .
- Point D2 was not earned. The value for L_2 is not between 0.026 H and 0.032 H.

Sample Identifier: PCEM Sample 3G**Score: 4**

- Point A1 was not earned. The response does not indicate that the potential difference over time was measured.
- Point A2 was not earned. The response does not indicate a method to reduce uncertainty.
- Point B1 was not earned. The response does not indicate two variables that will produce a linear graph.
- Point B2 was not earned. The response does not indicate the use of a feature of the linear graph to find L_1 .
- Point C1 was earned. The response indicates that the (negative) current and the derivative of the current with respect to time are the quantities to graph to produce a linear graph.
- Point C2 was earned. The response includes appropriate labels with units on the axes, and the graph has a linear scale.
- Point C3 was earned. The points plotted on the graph are consistent with the quantities in Table 2.
- Point C4 was earned. The response includes a best-fit line that approximates the trend of the plotted data.
- Point D1 was not earned. The response does not indicate how the slope of the best-fit line is related to L_2 .
- Point D2 was not earned. The value for L_2 is not between 0.026 H and 0.032 H.

Sample Identifier: PCEM Sample 3H**Score: 3**

- Point A1 was earned. The response does indicate that the potential difference over time was measured.
- Point A2 was earned. The response indicates that multiple trials could be used to reduce uncertainty.
- Point B1 was not earned. The response does not indicate two variables that will produce a linear graph allowing the determination of L_1 .
- Point B2 was not earned. The response does not indicate the use of a feature of a linear graph to find L_1 .
- Point C1 was not earned. The response indicates that the emf and the time are the quantities to graph to produce a linear graph to determine L_2 which is incorrect.
- Point C2 was not earned. The response includes appropriate labels with units on the axes, but the horizontal axis does not have a linear scale.
- Point C3 was not earned. There are no times listed that can be plotted.
- Point C4 was earned. The response includes a best-fit line that approximates the trend of the plotted data.

- Point D1 was not earned. The response does not correctly indicate how the slope of the best-fit line is related to L_2 .
- Point D2 was not earned. The response does not contain a value for L_2 between 0.026 H and 0.032 H.