2024

AP® Physics C: Electricity and Magnetism

Sample Student Responses and Scoring Commentary Set 1

Inside:

Free-Response Question 2

☑ Scoring Guidelines

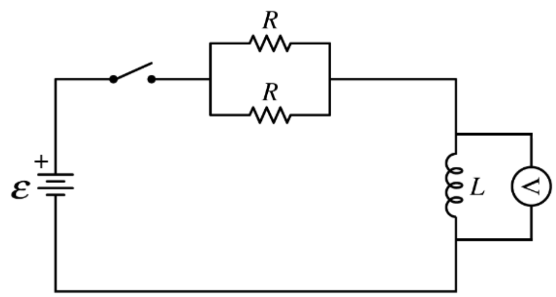
☑ Student Samples

☑ Scoring Commentary

Question 2: Free-Response Question — 15 points

(a)(i)	For correctly placing the voltmeter in parallel with the inductor	**1 point**

Example Response



(a)(ii)	For a procedure that indicates that the voltmeter should be used to measure the potential difference for at least one time	**1 point**
	For measuring the potential difference from immediately after the switch is closed to when steady-state conditions have been established or during a time interval that would allow the time constant to be determined	**1 point**

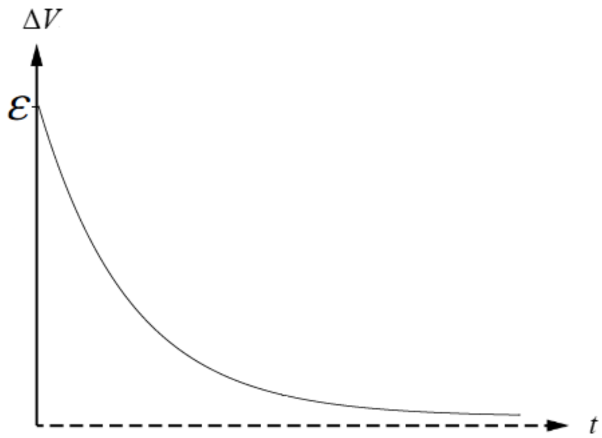
Example Response

Close the switch. Using the voltmeter, record the potential difference as a function of time until steady-state conditions are established.

Total for part (a) 3 points

(b)(i)	For correctly labeling potential difference on the vertical axis and time on the horizontal axis	**1 point**
	For a concave-up and decreasing curve	**1 point**
	For a curve that asymptotically approaches zero, or a curve that starts at the origin and approaches a horizontal asymptote that is consistent with the placement of the voltmeter in the response in part (a)(i)	**1 point**
	For including a vertical intercept or a horizontal asymptote that is consistent with the placement of the voltmeter in the response in part (a)(i) that is correctly labeled as $\mathcal{E}$	**1 point**

Example Response



(b)(ii) For indicating that a curve fit to the graph is that of an exponential function or for correctly relating the area under the curve to the current in the circuit — **1 point**

Alternate Solution

For indicating the time on the graph where the potential difference is approximately $0.37\mathcal{E}$ *, or* $0.63\mathcal{E}$ *for a curve that starts at the origin and approaches a horizontal asymptote that is consistent with the placement of the voltmeter in the response in part (a)(i)*

For indicating that the coefficient in front of the t of the curve-fit equation is equal to $\frac{R}{2L}$ or for correctly relating R to L and the current — **1 point**

Alternate Solution

For indicating that the time constant is equal to $\frac{2L}{R}$

Example Response

The data in the graph should be fit with an exponential function for the equation $V_L = \mathcal{E}\left(e^{-t\frac{R}{2L}}\right)$. *Because* $\mathcal{E}$ *and* L *are known,* R *can be calculated.*

Alternate Example Response

The potential difference at $0.37\mathcal{E}$ *along the vertical axis corresponds to the time constant along the horizontal axis. Because the time constant is equal to* $\frac{2L}{R}$, *and* L *is known,* R *can be calculated.*

Total for part (b) 6 points

(c) For a multi-step derivation that begins with an attempt at using Kirchhoff's loop rule **1 point**

Example Response

$\mathcal{E} - \Delta V_R - \Delta V_L = 0$

For indicating that the potential difference across the parallel combination of resistors is $I\left(\frac{R}{2}\right)$ **1 point**

For indicating that the absolute value of the potential difference across the inductor is $L\frac{dI}{dt}$ **1 point**

Example Solution

$$\mathcal{E} - \Delta V_R - \Delta V_L = 0$$
$$\mathcal{E} - I\left(\frac{R}{2}\right) - L\frac{dI}{dt} = 0$$
$$\frac{\mathcal{E}}{L} - \frac{IR}{2L} = \frac{dI}{dt}$$
$$-\frac{R}{L}\left(\frac{I}{2} - \frac{\mathcal{E}}{R}\right) = \frac{dI}{dt}$$

Total for part (c) 3 points

(d) For selecting $|\Delta V_2| > |\Delta V_1|$ with an attempt at a relevant justification **1 point**

For indicating that the potential difference across the original inductor is zero when steady-state conditions are established **1 point**

For indicating that the potential difference across the inductor of nonnegligible resistance is nonzero when steady-state conditions are established **1 point**

Example Response

$|\Delta V_2| > |\Delta V_1|$. *The potential difference* ΔV_1 *across the original, ideal inductor is zero at steady state. The potential difference across the new inductor would be nonzero due to the inductor's nonnegligible resistance. The value of* $|\Delta V_2|$ *would be the product of the steady-state current and the inductor's resistance.*

Total for part (d) 3 points

Total for question 2 15 points

Question 2

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

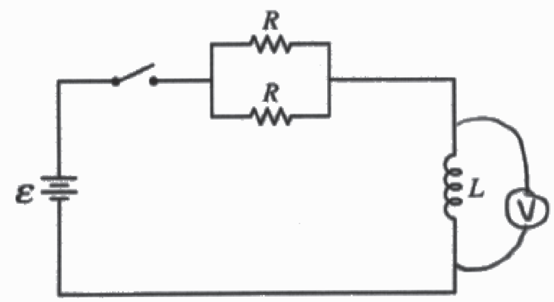


Figure 1

2. Students are asked to determine the resistance R of two identical resistors. The resistors are in parallel with each other and are connected in series to a battery of known emf $\mathcal{E}$, an inductor of known inductance L, and a switch, as shown in Figure 1. The students have access to a voltmeter that can measure potential difference as a function of time. The students are required to measure a quantity that decreases with time to determine R.

(a)

i. On the circuit diagram shown in Figure 1, **draw** the voltmeter, using the following symbol, with connections that would allow the students to correctly measure a potential difference that decreases with time.

Voltmeter Symbol

ii. **Describe** a procedure for collecting data that would allow the students to graphically determine the experimental value for R using the measured quantity that decreases with time. Provide enough detail so that another student could replicate the experiment.

- Using the voltmeter, plot a graph of Voltage with respect to time starting at $t=0$ when the switch is closed
- Find the time when the voltage across the inductor is approximately 37% of $\mathcal{E}$ ~~or~~ voltage when $t=0$
- This time is the time constant $\tau = \frac{L}{R_{eq}}$. Using the equation, evaluate $R_{eq} = \frac{1}{\frac{1}{R}+\frac{1}{R}} = \frac{1}{2}R = \frac{L}{\tau} \rightarrow R = \frac{2L}{\tau}$

Question 2

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

(b)

i. On the axes shown in Figure 2, produce a graph that represents the expected trend of the data by completing the following tasks.

- **Label** the quantities graphed on the vertical and horizontal axes.
- **Sketch** a line or curve that represents the expected trend of the collected data.
- **Label** any appropriate intercepts and/or asymptotes in terms of the quantities provided.

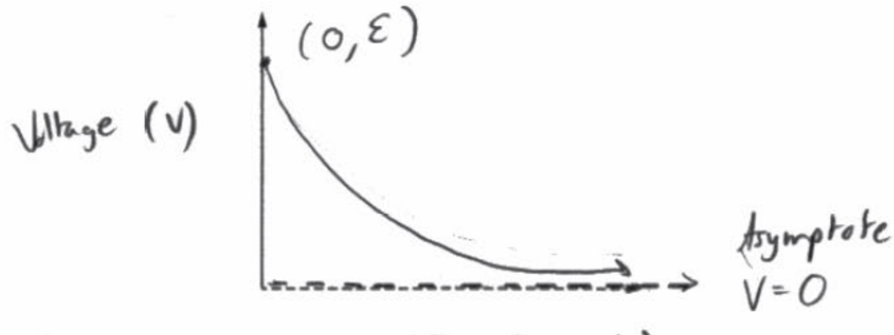


Figure 2

ii. **Describe** how the information from the graph in part (b)(i) would be used to determine the experimental value for *R*.

Find the time when voltage is approximate $\frac{\varepsilon}{e}$ or 0.37ε. Setting this time equal to the time constant gets $\tau = \frac{L}{R_{eq}}$ where $R_{eq} = \frac{1}{\frac{1}{R} + \frac{1}{R}} = \frac{1}{2}R$. Solving for R gets

$R = \frac{2L}{\tau}$

Question 2

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

(c) Starting with an appropriate application of Kirchhoff's loop rule, **derive**, but do NOT solve, a differential equation that can be used to determine the current I in the inductor at time t after the switch is closed. Express your answer in terms of R, $\mathcal{E}$, L, t, and physical constants, as appropriate.

$$\mathcal{E} - \frac{IR}{2} - L\frac{dI}{dt} = 0$$

$$R_{eq} = \frac{1}{\frac{1}{R} + \frac{1}{R}} = \frac{R}{2}$$

After reaching steady state, the absolute value of the potential difference across the inductor is $|\Delta V_1|$. The students replace the original inductor with a new inductor that has nonnegligible resistance. The experiment is repeated. After a long time, the absolute value of the potential difference across the new inductor is $|\Delta V_2|$.

(d) **Indicate** whether $|\Delta V_2|$ is greater than, less than, or equal to $|\Delta V_1|$.

✓ $|\Delta V_2| > |\Delta V_1|$ ____ $|\Delta V_2| < |\Delta V_1|$ ____ $|\Delta V_2| = |\Delta V_1|$

Justify your answer.

For the ideal inductor, $|\mathcal{E}| = L\frac{dI}{dt}$.

At steady state $\frac{dI}{dt} = 0$ so $|\mathcal{E}| = 0$

Since the new inductor has resistance, and a current will be present, it will have a voltage greater than 0

Question 2

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

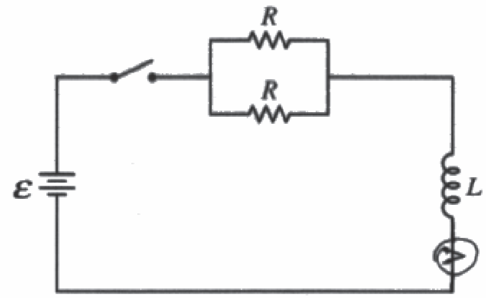


Figure 1

2. Students are asked to determine the resistance R of two identical resistors. The resistors are in parallel with each other and are connected in series to a battery of known emf $\mathcal{E}$, an inductor of known inductance L, and a switch, as shown in Figure 1. The students have access to a voltmeter that can measure potential difference as a function of time. The students are required to measure a quantity that decreases with time to determine R.

(a)

i. On the circuit diagram shown in Figure 1, **draw** the voltmeter, using the following symbol, with connections that would allow the students to correctly measure a potential difference that decreases with time.

Voltmeter Symbol

ii. **Describe** a procedure for collecting data that would allow the students to graphically determine the experimental value for R using the measured quantity that decreases with time. Provide enough detail so that another student could replicate the experiment.

1. place voltmeter in series with the inductor so that it is after it.

2. Close the switch and allow the Circuit to reach steady State

3. take data measured by voltmeter and graph it.

Question 2

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

(b)

i. On the axes shown in Figure 2, produce a graph that represents the expected trend of the data by completing the following tasks.

- **Label** the quantities graphed on the vertical and horizontal axes.
- **Sketch** a line or curve that represents the expected trend of the collected data.
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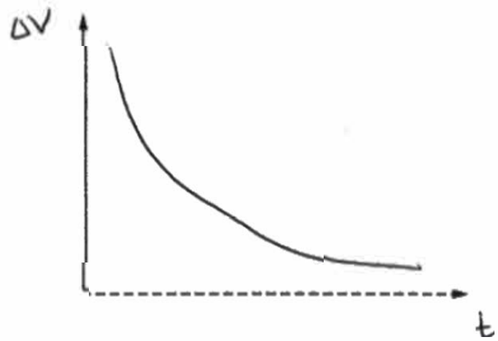

Figure 2

ii. **Describe** how the information from the graph in part (b)(i) would be used to determine the experimental value for *R*.

I'm not sure man I don't think it can.

Question 2

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

(c) Starting with an appropriate application of Kirchhoff's loop rule, **derive**, but do NOT solve, a differential equation that can be used to determine the current I in the inductor at time t after the switch is closed. Express your answer in terms of R, $\mathcal{E}$, L, t, and physical constants, as appropriate.

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

$$\int \mathcal{E}\, dt = \int -L\, dI$$

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

$$I = \frac{\mathcal{E}(t)}{-L}$$

After reaching steady state, the absolute value of the potential difference across the inductor is $|\Delta V_1|$. The students replace the original inductor with a new inductor that has nonnegligible resistance. The experiment is repeated. After a long time, the absolute value of the potential difference across the new inductor is $|\Delta V_2|$.

(d) **Indicate** whether $|\Delta V_2|$ is greater than, less than, or equal to $|\Delta V_1|$.

X $|\Delta V_2| > |\Delta V_1|$ ____ $|\Delta V_2| < |\Delta V_1|$ ____ $|\Delta V_2| = |\Delta V_1|$

Justify your answer.

Because ~~the~~ the new Inductor has non negligible resistance, it takes more energy for each charge to cross. thus, there is a higher potential difference.

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Question 2

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

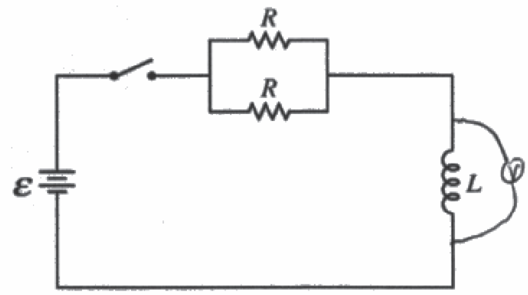

Figure 1

2. Students are asked to determine the resistance R of two identical resistors. The resistors are in parallel with each other and are connected in series to a battery of known emf $\mathcal{E}$, an inductor of known inductance L, and a switch, as shown in Figure 1. The students have access to a voltmeter that can measure potential difference as a function of time. The students are required to measure a quantity that decreases with time to determine R.

(a)

i. On the circuit diagram shown in Figure 1, **draw** the voltmeter, using the following symbol, with connections that would allow the students to correctly measure a potential difference that decreases with time.

Voltmeter Symbol

ii. **Describe** a procedure for collecting data that would allow the students to graphically determine the experimental value for R using the measured quantity that decreases with time. Provide enough detail so that another student could replicate the experiment.

I will close the switch, and measure how much current changes in a specified time, like 1 second. Using that, I can calculate the change in current over time. Once the circuit reaches equilibrium I will calculate the I through the circuit by dividing $\mathcal{E}$ by $\frac{R}{2}$.

Question 2

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

(b)

i. On the axes shown in Figure 2, produce a graph that represents the expected trend of the data by completing the following tasks.

- **Label** the quantities graphed on the vertical and horizontal axes.
- **Sketch** a line or curve that represents the expected trend of the collected data.
- **Label** any appropriate intercepts and/or asymptotes in terms of the quantities provided.

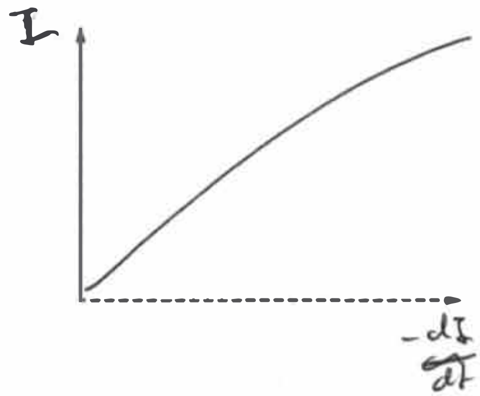

Figure 2

ii. **Describe** how the information from the graph in part (b)(i) would be used to determine the experimental value for *R*.

Slope $= \frac{L}{R}$

Question 2

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

(c) Starting with an appropriate application of Kirchhoff's loop rule, **derive**, but do NOT solve, a differential equation that can be used to determine the current I in the inductor at time t after the switch is closed. Express your answer in terms of R, $\mathcal{E}$, L, t, and physical constants, as appropriate.

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

After reaching steady state, the absolute value of the potential difference across the inductor is $|\Delta V_1|$. The students replace the original inductor with a new inductor that has nonnegligible resistance. The experiment is repeated. After a long time, the absolute value of the potential difference across the new inductor is $|\Delta V_2|$.

(d) **Indicate** whether $|\Delta V_2|$ is greater than, less than, or equal to $|\Delta V_1|$.

____ $|\Delta V_2| > |\Delta V_1|$ ____ $|\Delta V_2| < |\Delta V_1|$ ✓ $|\Delta V_2| = |\Delta V_1|$

Justify your answer.

After a long time, the inductor will come to have the same of total emf in the battery, Thus $V_L = V_1$

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:

- Calculate the equivalent resistance of a parallel circuit.
- Determine the potential difference across an inductor in a LR circuit at $t = 0$ and $t = \infty$.
- Identify the placement of a voltmeter to illustrate a decreasing potential difference over time as the inductor is energized.
- Apply Kirchhoff's loop rule to an LR circuit.
- Graphically model the behavior of an LR circuit to determine a best curve-fit to the data chosen.
- Derive an expression for the resistance in an LR circuit based on experimental data and a known inductance value.
- Sketch a graph that shows a functional relationship between potential difference and time across an inductor in a LR circuit.
- Select and plot data from an experimental procedure to represent a decreasing measured quantity.
- Linearize exponential data and/or determine the best-fit curve of exponential data.
- Determine and justify the relationship between the voltages of an ideal inductor and an inductor with internal resistance.

Sample: 2A
Score: 15

Part (a) earned 3 points. The first point was earned for correctly indicating that the voltmeter is in parallel with the inductor. The second point was earned for indicating that potential difference measurements were taken at least once. The third point was earned for indicating that the switch was closed, and potential difference data was recorded until steady-state conditions had been established. Part (b) earned 6 points. The first point was earned for correctly labeling the y-axis (potential difference or voltage) and x-axis (time). The second point was earned for correctly including a concave-up and decreasing curve. The third point was earned for including a curve that asymptotically approaches zero. The fourth point was earned for including a vertical intercept that is correctly labeled as $\mathcal{E}$. The fifth point was earned for indicating the time on the graph when the potential difference is approximately $0.37\mathcal{E}$. The sixth point was earned for indicating that the time constant is equal to $\frac{2L}{R}$. Part (c) earned 3 points. The first point was earned for including a multi-step derivation of Kirchhoff's loop rule. The second point was earned for indicating a correct response for the potential difference across the resistor. The third point was earned for indicating a correct response for the potential difference across the inductor. Part (d) earned 3 points. The first point was earned for selecting $|\Delta V_2| > |\Delta V_1|$ with a relevant justification. The second point was earned for indicating that the original inductor had zero potential difference across it. The third point was earned for indicating that the potential difference across the new inductor of nonnegligible resistance is nonzero when steady-state conditions are established.

Question 2 (continued)

Sample: 2B
Score: 7

Part (a) earned 2 points. The first point was not earned because the response does not correctly indicate that the voltmeter is in parallel with the inductor; the voltmeter is in series with the inductor. The second point was earned for indicating that potential difference measurements were taken at least once. The third point was earned for indicating that the switch was closed, and potential difference data was recorded until steady-state conditions had been established. Part (b) earned 3 points. The first point was earned for correctly labeling the y-axis (potential difference or voltage) and x-axis (time). The second point was earned for correctly including a concave-up and decreasing curve. The third point was earned for including a curve that asymptotically approaches zero. The fourth point was not earned because the response does not include a vertical intercept that is correctly labeled as $\mathcal{E}$. The fifth point was not earned because the response does not indicate a curve fit to an exponential function or the time on the graph when the potential difference is approximately $0.37\mathcal{E}$. The sixth point was not earned because the response does not indicate the coefficient in front of t or the time constant is equal to $\frac{2L}{R}$. Part (c) earned 1 point. The first point was not earned because the response does not include a multi-step derivation of Kirchhoff's loop rule. The second point was not earned because the response does not indicate a correct response for the potential difference across the resistor. The third point was earned for indicating a correct response for the potential difference across the inductor. Part (d) earned 1 point for selecting $|\Delta V_2| > |\Delta V_1|$ with a relevant justification. The second point was not earned because the response does not indicate that the original inductor had zero potential difference across its. The third point was not earned because the response does not indicate that the potential difference across the new inductor of nonnegligible resistance is nonzero when steady-state conditions are established.

Sample: 2C
Score: 2

Part (a) earned 1 point for correctly indicating that the voltmeter is in parallel with the inductor. The second point was not earned because the procedure does not indicate that potential difference measurements were taken at least once. The third point was not earned because the response does not indicate that the switch was closed, and that potential difference data was recorded until steady-state conditions had been established. Part (b) did not earn any points. The first point was not earned because the response does not correctly label the y-axis (potential difference or voltage) and x-axis (time). The second point was not earned because the response does not correctly include a concave-up and decreasing curve. The third point was not earned because the response does not include a curve that asymptotically approaches zero. The fourth point was not earned because the response does not include a vertical intercept that is correctly labeled as $\mathcal{E}$. The fifth point was not earned because the response does not indicate a curve fit to a graph of an exponential function or the time on the graph when the potential difference is approximately $0.37\mathcal{E}$. The sixth point was not earned because the response does not indicate the coefficient of t or that the time constant is equal to $\frac{2L}{R}$. Part (c) earned 1 point. The first point was not earned because the response does not include a multi-step derivation of Kirchhoff's loop rule. The second point was not earned because the response does not indicate a correct response for the potential difference across the resistor. The third point was earned for indicating a correct response for the potential difference across the inductor. Part (d) did not earn any points. The first point was not earned because the response does not select $|\Delta V_2| > |\Delta V_1|$ with a relevant justification. The second point was not earned because the response does not indicate that the original inductor had zero potential difference across it. The third point was not earned because the response does not indicate that the potential difference across the new inductor of nonnegligible resistance is nonzero when steady-state conditions are established.