

2024



AP[®] Physics C: Electricity and Magnetism

Scoring Guidelines Set 1

Question 1: Free-Response Question**15 points**

- (a) For using a correct equation for electric flux **1 point**

Example Response

$$\Phi_E = \frac{Q}{\epsilon_0}$$

- For the correct numerical answer **1 point**

Scoring Note: This point can be earned if a negative sign is included in the final answer or if units are missing and/or the units are incorrect.

Example Response

$$|\Phi_E| = 226 \frac{\text{N} \cdot \text{m}^2}{\text{C}}$$

Example Solution

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q}{\epsilon_0}$$

$$\Phi_E = \frac{Q}{\epsilon_0}$$

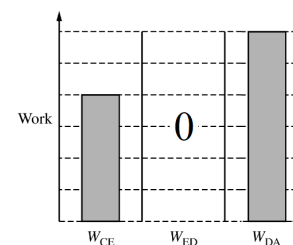
$$\Phi_E = \frac{-2.0 \times 10^{-9} \text{ C}}{8.85 \times 10^{-12} \frac{\text{C}^2}{\text{N} \cdot \text{m}^2}}$$

$$|\Phi_E| = 226 \frac{\text{N} \cdot \text{m}^2}{\text{C}}$$

Total for part (a) 2 points

- (b)(i) For indicating that $W_{\text{ED}} = 0$ **1 point**

- For drawing a bar representing W_{DA} that has a height of six units **1 point**

Example Response

(b)(ii) For using an equation that relates the electric field to potential difference **1 point**

Scoring Note: This point can be earned if the response begins with a correct relationship between electric field and potential difference in which numerical values are already substituted.

Example Responses

$$E_x = -\frac{dV}{dx} \quad \text{OR} \quad |E_x| = \left| -\frac{dV}{dx} \right| \quad \text{OR} \quad |E_x| = \left| -\frac{\Delta V}{\Delta x} \right| \quad \text{OR} \quad \Delta V = -\int \vec{E} \cdot d\vec{r}$$

For correct substitutions of values of electric potential and the distance between equipotential lines that can be used to calculate the approximate magnitude of the electric field at Position B **1 point**

Example Response

$$|E_x| = \left| -\frac{20.0 \text{ V} - 0.0 \text{ V}}{0.65 \text{ m}} \right|$$

Example Solution

$$\begin{aligned} E_x &= -\frac{dV}{dx} \\ |E_x| &= \left| -\frac{dV}{dx} \right| \\ |E_x| &= \left| -\frac{\Delta V}{\Delta x} \right| \\ |E_x| &= \left| -\frac{20.0 \text{ V} - 0.0 \text{ V}}{0.65 \text{ m}} \right| \\ |E_x| &= 31 \frac{\text{V}}{\text{m}} \end{aligned}$$

Total for part (b) 4 points

(c) For selecting only +y with an attempt at a relevant justification **1 point**

For indicating that the direction of the electric field vector is perpendicular to a line that is tangent to the equipotential line at Position D **1 point**

For indicating one of the following: **1 point**

- The test charge moves from a higher electric potential to a lower electric potential.
- The test charge and the sphere have charges of opposite sign.
- The test charge moves in the direction of the electric field, which is directed upward.

Example Response

+y. The direction of an electric field vector is perpendicular to an equipotential line. Because the test charge has a positive charge, the test charge would move from a position of higher electric potential to a position of lower electric potential when an electric force is exerted on the test charge. Therefore, at Position D, the electric force is upward because that is the direction that is perpendicular to the equipotential line and in the direction of decreasing electric potential.

Total for part (c) 3 points

(d)(i) For using an appropriate equation for determining the electric potential from a line of uniform charge **1 point**

Example Responses

$$V = \frac{1}{4\pi\epsilon_0} \sum \frac{q_i}{r_i} \quad \text{OR} \quad V = \frac{1}{4\pi\epsilon_0} \int \frac{dq}{r} \quad \text{OR} \quad \Delta V = -\int \vec{E} \cdot d\vec{r}$$

For a correct determination of r , the distance between Point P and a point on the line of uniform charge **1 point**

Example Responses

$$V_P = k \sum \frac{Q}{x_P - x} \quad \text{OR} \quad V_P = k \int \left(\frac{1}{x_P - x} \right) dq$$

For a correct integral with λdx substituted for dq **1 point**

Example Response

$$V_P = k\lambda \int \left(\frac{1}{x_P - x} \right) dx$$

For the correct limits of integration **1 point**

Example Response

$$V_P = k\lambda \int_0^{4L} \left(\frac{1}{x_P - x} \right) dx$$

Example Solutions

$$V = \frac{1}{4\pi\epsilon_0} \sum \frac{q_i}{r_i}$$

$$V_P = k \int \left(\frac{1}{x_P - x} \right) dq$$

$$dq = \lambda dx$$

$$V_P = k\lambda \int \left(\frac{1}{x_P - x} \right) dx$$

$$V_P = k\lambda \int_0^{4L} \left(\frac{1}{x_P - x} \right) dx$$

$$V_P = -k\lambda \ln(x_P - x) \Big|_0^{4L} = k\lambda \ln(x_P - x) \Big|_{4L}^0$$

$$V_P = k\lambda \ln \left(\frac{x_P}{x_P - 4L} \right)$$

OR

$$\Delta V = - \int \vec{E} \cdot d\vec{r}$$

$$E(x) = \int \frac{k}{r^2} dq$$

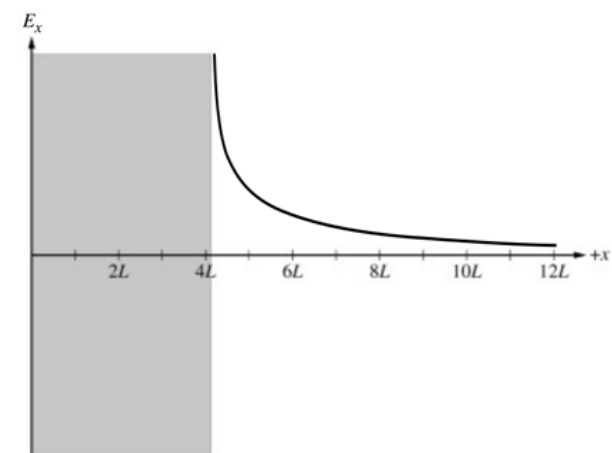
$$E(x) = \int_0^{4L} \frac{k\lambda}{(x - x')^2} dx' = k\lambda \left(\frac{1}{x - 4L} - \frac{1}{x} \right)$$

$$V_P = - \int_{\infty}^{x_P} E(x) dx = -k\lambda \int_{\infty}^{x_P} \left(\frac{1}{x - 4L} - \frac{1}{x} \right) dx$$

$$V_P = k\lambda \ln \left(\frac{x_P}{x_P - 4L} \right)$$

(d)(ii) For sketching a curve or line that continually approaches the horizontal axis as position increases **1 point**

For sketching a concave up curve that is always positive **1 point**

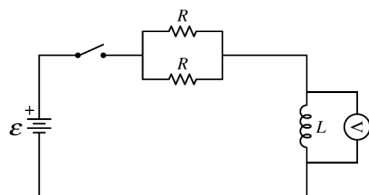
Example Response

Total for part (d) 6 points

Total for question 1 15 points

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.

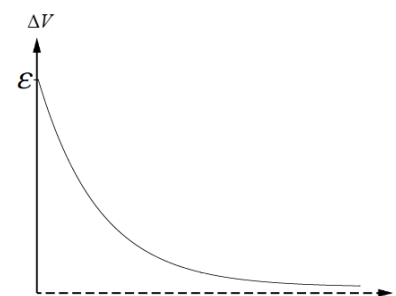
Total for part (a) 3 points

- (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 $\frac{R}{2L}$ **1 point**

or for correctly relating R to L and the current

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

$$V_L = \mathcal{E} \left(e^{-t \frac{R}{2L}} \right). \text{ Because } \mathcal{E} \text{ and } L \text{ are known, } R \text{ can be calculated.}$$

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 **1 point**

$$I\left(\frac{R}{2}\right)$$

- 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

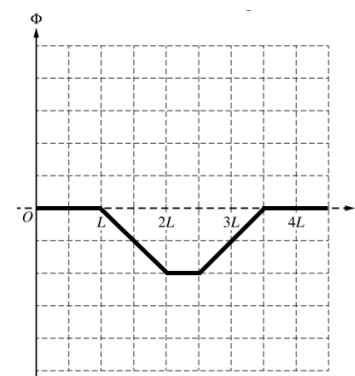
Question 3: Free-Response Question**15 points**

- (a) For a sketch that indicates that the magnetic flux is zero from $x = 0$ to $x = L$ and for the region $x > 3.5L$ **1 point**

- For a sketch that indicates that the absolute value of the magnetic flux increases with a constant slope in the region $L < x < 2L$ **1 point**

- For a sketch that indicates that the magnetic flux is constant and nonzero in the region $2L < x < 2.5L$ **1 point**

- For a sketch that indicates that the absolute value of the magnetic flux decreases from a nonzero value at $x = 2.5L$ to zero at $x = 3.5L$ **1 point**

Example Response

Scoring Note: A sketch that is reflected across the horizontal axis can earn the four points.

Scoring Note: The absolute values of the slopes in regions $L < x < 2L$ and $2.5L < x < 3.5L$ are not considered for earning points in the response in part (a).

Total for part (a) 4 points

- (b)(i) For selecting Counterclockwise with an attempt at a relevant justification **1 point**
For indicating the magnetic flux through the loop is increasing in the $-z$ -direction **1 point**

OR

- For indicating the magnetic field due to the induced current will be directed in the $+z$ -direction

Example Response

Counterclockwise. The magnetic flux through the loop is increasing in the $-z$ -direction. Therefore, a magnetic field is induced by the current in the loop to oppose the increasing magnetic flux. To establish this field, the current must be counterclockwise.

(b)(ii) For a multistep derivation that includes Faraday’s law **1 point**

Scoring Note: The point can be earned if a negative sign is not included.

Example Response

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

For indicating $\frac{dA}{dt}$ is $2Lv$ **1 point**

Scoring Note: The point can be earned if a negative sign is included.

Example Response

$$\mathcal{E} = B\frac{dA}{dt} = 2BLv$$

For using Ohm’s law, resulting in an expression for I_R that is consistent with the expression determined for the emf $\mathcal{E}$ **1 point**

Scoring Note: The point can be earned if a negative sign is included.

Example Response

$$I_R = \frac{2BLv}{R}$$

Example Solution

$$\mathcal{E} = -\frac{d\Phi_B}{dt}$$

$$\mathcal{E} = -\frac{d}{dt}\left(\int \vec{B} \cdot d\vec{A}\right)$$

$$\mathcal{E} = -\frac{d}{dt}(BA) = -\frac{d}{dt}(-B(2L)x)$$

$$\mathcal{E} = 2BL\frac{dx}{dt}$$

$$\mathcal{E} = 2BLv$$

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

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

$$I_R = \frac{2BLv}{R}$$

(b)(iii) For using a correct general expression for P **1 point**

Example Responses

$$P = I^2R \quad \text{OR} \quad P = \frac{(\Delta V)^2}{R} \quad \text{OR} \quad P = I\Delta V$$

For an expression for P that is consistent with the response in part (b)(ii) that is in terms of the provided quantities only **1 point**

Example Response

$$P = \frac{4B^2L^2v^2}{R}$$

Example Solution

$$P = I^2R$$

$$P = \frac{(2BLv)^2}{R}$$

$$P = \frac{4B^2L^2v^2}{R}$$

Total for part (b) 7 points

(c) For selecting $E_{\text{new}} < E_{\text{original}}$ with an attempt at a relevant justification **1 point**

For indicating one of the following: **1 point**

- The change in magnetic flux is greater for the original scenario.
- The induced current occurs for a greater amount of time in the original scenario.
- The induced emf occurs for a greater amount of time in the original scenario.

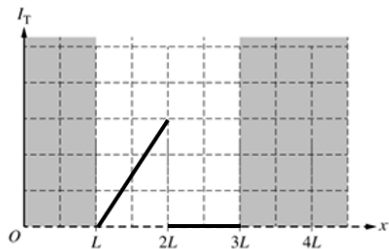
Example Response

The change in magnetic flux is greater in the original scenario, which produces an emf and current for a longer time. Therefore, $E_{\text{new}} < E_{\text{original}}$.

Total for part (c) 2 points

- | | | |
|-----|--|---------|
| (d) | For a sketch that has an absolute value that only increases from $x = L$ to $x = 2L$ | 1 point |
| | For a sketch that is zero from $2L$ to $3L$ | 1 point |

Example Response



Scoring Note: A response that is reflected across the horizontal axis earns both points.

Scoring Note: Any portion of the graph before $x = L$ and after $x = 3L$ are not scored.

Total for part (d) 2 points

Total for question 3 15 points