2024

AP® Physics C: Electricity and Magnetism

Scoring Guidelines
Set 1

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Question 1: Free-Response Question — 15 points

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

Example Response

$$\Phi_E = \frac{Q}{\varepsilon_0}$$

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

$$\oint \vec{E}\cdot d\vec{A} = \frac{Q}{\varepsilon_0}$$

$$\Phi_E = \frac{Q}{\varepsilon_0}$$

$$\Phi_E = \frac{-2.0\times10^{-9}\ \text{C}}{8.85\times10^{-12}\ \frac{\text{C}^2}{\text{N}\cdot\text{m}^2}}$$

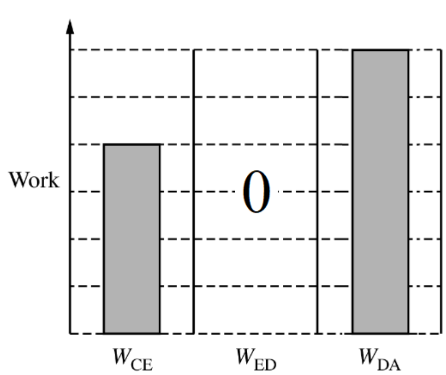
$$|\Phi_E| = 226\,\frac{\text{N}\cdot\text{m}^2}{\text{C}}$$

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



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(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

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

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

$$E_x = -\frac{dV}{dx}$$

$$|E_x| = \left|-\frac{dV}{dx}\right|$$

$$|E_x| = \left|-\frac{\Delta V}{\Delta x}\right|$$

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

$$|E_x| = 31\,\frac{\text{V}}{\text{m}}$$

Total for part (b) 4 points

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(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: • 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.	**1 point**

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

$$V = \frac{1}{4\pi\varepsilon_0}\sum\frac{q_i}{r_i} \quad \textbf{OR} \quad V = \frac{1}{4\pi\varepsilon_0}\int\frac{dq}{r} \quad \textbf{OR} \quad \Delta V = -\int\vec{E}\cdot d\vec{r}$$

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

Example Responses

$$V_\text{P} = k\sum\frac{Q}{x_\text{P} - x} \quad \textbf{OR} \quad V_\text{P} = k\int\left(\frac{1}{x_\text{P} - x}\right)dq$$

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

Example Response

$$V_\text{P} = k\lambda\int\left(\frac{1}{x_\text{P} - x}\right)dx$$

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

Example Response

$$V_\text{P} = k\lambda\int_0^{4L}\left(\frac{1}{x_\text{P} - x}\right)dx$$

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Example Solutions

$$V = \frac{1}{4\pi\varepsilon_0}\sum\frac{q_i}{r_i}$$

$$V_{\text{P}} = k\int\left(\frac{1}{x_{\text{P}} - x}\right)dq$$

$$dq = \lambda\, dx$$

$$V_{\text{P}} = k\lambda\int\left(\frac{1}{x_{\text{P}} - x}\right)dx$$

$$V_{\text{P}} = k\lambda\int_0^{4L}\left(\frac{1}{x_{\text{P}} - x}\right)dx$$

$$V_{\text{P}} = -k\lambda\ln(x_{\text{P}} - x)\,\Big|_0^{4L} = k\lambda\ln(x_{\text{P}} - x)\,\Big|_{4L}^{0}$$

$$V_{\text{P}} = k\lambda\ln\left(\frac{x_{\text{P}}}{x_{\text{P}} - 4L}\right)$$

OR

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

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

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

$$V_{\text{P}} = -\int_\infty^{x_{\text{P}}}E(x)\,dx = -k\lambda\int_\infty^{x_{\text{P}}}\left(\frac{1}{x - 4L} - \frac{1}{x}\right)dx$$

$$V_{\text{P}} = k\lambda\ln\left(\frac{x_{\text{P}}}{x_{\text{P}} - 4L}\right)$$

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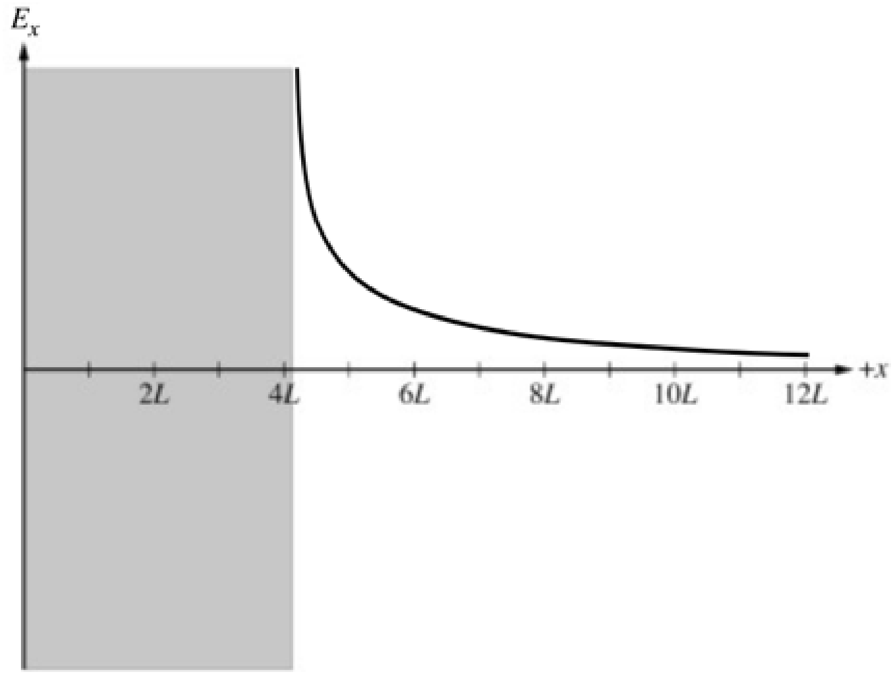
(d)(ii)	For sketching a curve or line that continually approaches the horizontal axis as position increases	**1 point**
	For sketching a concave up curve that is always positive	**1 point**

Example Response



Total for part (d) 6 points

Total for question 1 15 points

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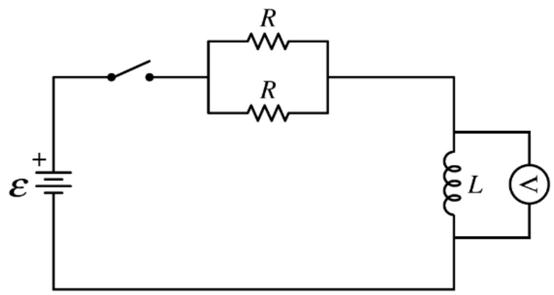
Question 2: Free-Response Question — 15 points

(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**

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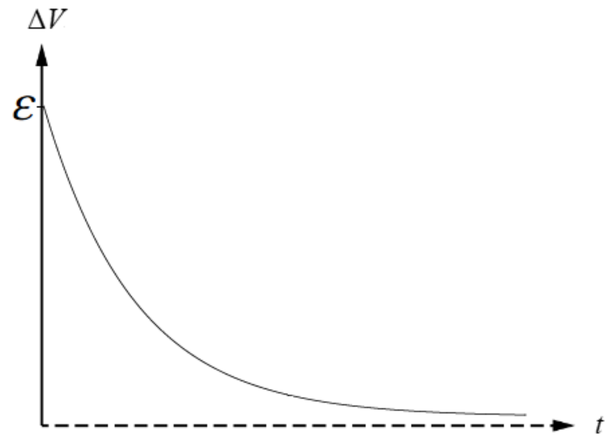
Example Response



(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 *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)*	**1 point**
	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 *Alternate Solution* *For indicating that the time constant is equal to* $\frac{2L}{R}$	**1 point**

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 $\lvert\Delta V_2\rvert > \lvert\Delta V_1\rvert$ 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 $\lvert\Delta V_2\rvert > \lvert\Delta V_1\rvert$. *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 $\lvert\Delta V_2\rvert$ 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**

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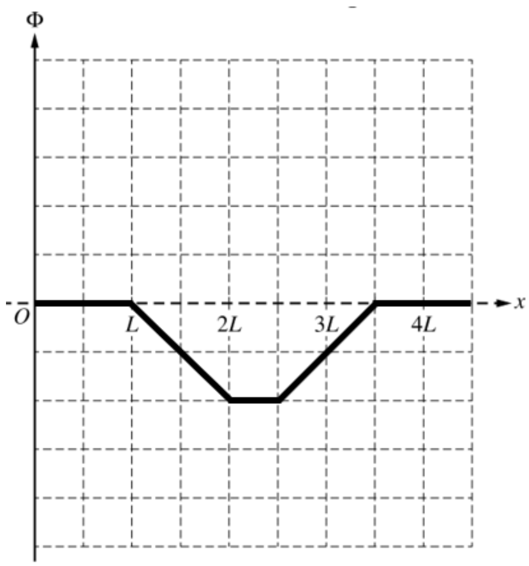
Question 3: Free-Response Question — 15 points

(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 $L < x < 2D$ 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 **OR** For indicating the magnetic field due to the induced current will be directed in the $+z$-direction	**1 point**

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

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

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

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

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

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

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

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

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

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

Example Responses

$P = I^2R$ **OR** $P = \dfrac{(\Delta V)^2}{R}$ **OR** $P = I\Delta V$

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

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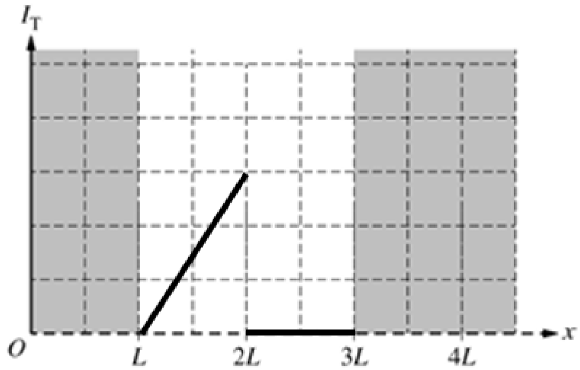
(d)	For a sketch that has an absolute value that only increases from $x = L$ to $x = 2L$	**1 point**
	For a sketch that is zero from $2L$ to $3L$	**1 point**

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