2024

AP® Physics C: Electricity and Magnetism

Scoring Guidelines

Set 2

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: Correct units are not required to earn this point.

Example Response

$$\Phi_E = 113\,\frac{\text{N}\cdot\text{m}^2}{\text{C}}$$

Example Solution

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

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

$$\Phi_E = \frac{1.0\times10^{-9}\ \text{C}}{8.85\times10^{-12}\,\frac{\text{C}^2}{\text{N}\cdot\text{m}^2}}$$

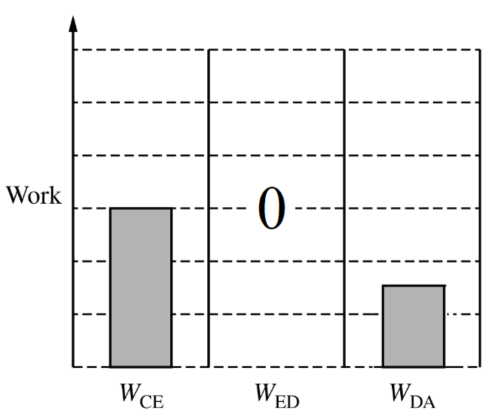
$$\Phi_E = 113\,\frac{\text{N}\cdot\text{m}^2}{\text{C}}$$

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 approximately one and a half 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

$$E_y = -\frac{dV}{dy} \quad \textbf{OR} \quad |E_y| = \left|-\frac{dV}{dy}\right| \quad \textbf{OR} \quad |E_y| = \left|-\frac{\Delta V}{\Delta y}\right| \quad \textbf{OR} \quad \Delta V = -\int \vec{E} \cdot d\vec{r}$$

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

$$|E_y| = \left|-\frac{-20.0\text{ V} - (-10.0\text{ V})}{1.4\text{ m}}\right|$$

Example Solution

$$E_y = -\frac{dV}{dy}$$

$$|E_y| = \left|-\frac{dV}{dy}\right|$$

$$|E_y| = \left|-\frac{\Delta V}{\Delta y}\right|$$

$$|E_y| = \left|-\frac{-20.0\text{ V} - (-10.0\text{ V})}{1.4\text{ m}}\right|$$

$$|E_y| = 7.1\,\frac{\text{V}}{\text{m}}$$

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 C — **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 rod have charges of the opposite sign.
- The test charge and the sphere have charges of the same sign.

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 C, the electric force is downward 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

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

For a correct integral with $\lambda\, dy$ substituted for dq **1 point**

Example Response

$$V_\text{P} = -k\lambda\int\left(\frac{1}{y_\text{P} - y}\right)dy$$

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

Example Response

$$V_\text{P} = -k\lambda\int_0^{2L}\left(\frac{1}{y_\text{P} - y}\right)dy$$

Example Solutions

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

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

$$dq = -\lambda\, dy$$

$$V_P = -k\lambda\int\left(\frac{1}{y_P - y}\right)dy$$

$$V_P = -k\lambda\int_0^{2L}\left(\frac{1}{y_P - y}\right)dy$$

$$V_P = k\lambda\ln(y_P - y)\,\Big|_0^{2L} = -k\lambda\ln(y_P - y)\,\Big|_{2L}^{0}$$

$$V_P = -k\lambda\ln\left(\frac{y_P}{y_P - 2L}\right)$$

OR

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

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

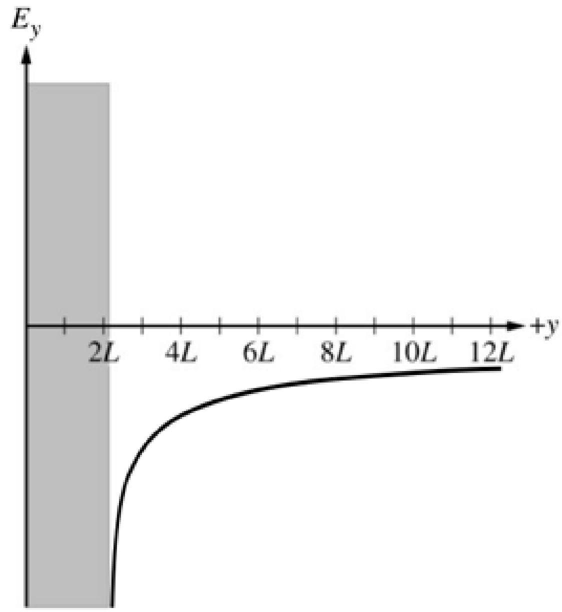
$$E(y) = \int_0^{2L}\frac{k\lambda}{(y - y')^2}\,dy' = k\lambda\left(\frac{1}{y - 2L} - \frac{1}{y}\right)$$

$$V_P = -\int_\infty^{y_P}E(y)\,dy = -k\lambda\int_\infty^{y_P}\left(\frac{1}{y - 2L} - \frac{1}{y}\right)dy$$

$$V_P = k\lambda\ln\left(\frac{y_P}{y_P - 2L}\right)$$

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

Example Response



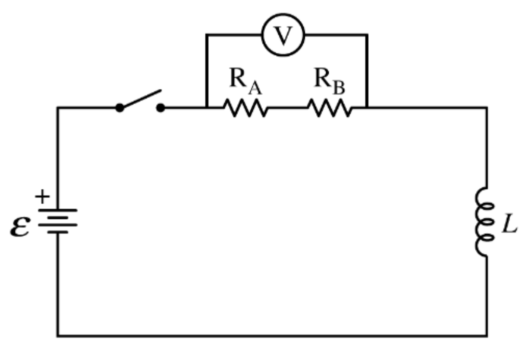
Total for part (d) 6 points

Total for question 1 15 points

Question 2: Free-Response Question — 15 points

(a)(i) For correctly placing the voltmeter in parallel with Resistor A , Resistor B , or the combination of resistors A and B — **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 until a time at which the time constant can 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

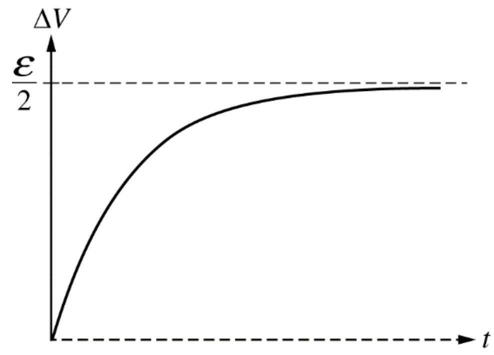
(b)(i) For correctly labeling potential difference on the vertical axis and time on the horizontal axis — **1 point**

For a concave-down and increasing curve — **1 point**

For a curve that starts at the origin and asymptotically approaches a nonzero potential difference value — **1 point**

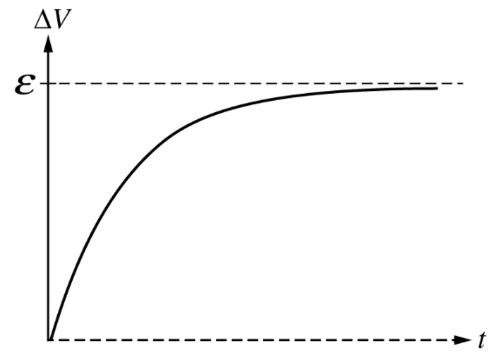
For correctly labeling the horizontal asymptote that is consistent with the indication of the connection of the voltmeter in the response in part (a)(i) — **1 point**

Example Responses



One Resistor

OR



Combination of Resistors

(b)(ii) For indicating that a curve fit to the graph is that of an exponential function **1 point**

Alternate Solution

For indicating the time on the graph where the potential difference across Resistor A *or Resistor* B *is approximately* $\frac{0.63\mathcal{E}}{2}$ *or that the potential difference across the combination of resistors* A *and* B *is approximately* $0.63\mathcal{E}$

For indicating that the coefficient in front of the t of the curve-fit equation is equal to $\frac{2R}{L}$ **1 point**

Alternate Solution

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

Example Response

The data in the graph should be fit with an exponential function for the equation $V_R = \mathcal{E}\left(1 - e^{-t\frac{2R}{L}}\right)$*. Because* $\mathcal{E}$ *and* L *are known,* R *can be calculated.*

Alternate Example Response

The potential difference at $0.63\mathcal{E}$ *along the vertical axis corresponds to the time constant along the horizontal axis. Because the time constant is equal to* $\frac{L}{2R}$*, 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 series combination of resistors is $I(2R)$	**1 point**
For indicating that the absolute value of the potential difference across the inductor is $L\dfrac{dI}{dt}$	**1 point**

Example Solution

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

$$\mathcal{E} - I(2R) - L\frac{dI}{dt} = 0$$

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

$$-\frac{R}{L}\left(2I - \frac{\mathcal{E}}{R}\right) = \frac{dI}{dt}$$

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 total resistance has increased	**1 point**
	For indicating that the current decreases due to the increased resistance	**1 point**

OR

For indicating that the potential difference across the inductor will increase, and, therefore, the potential difference across R_A must decrease

Example Response

$\lvert\Delta V_2\rvert < \lvert\Delta V_1\rvert$*, because the inductor has nonnegligible resistance, and the total resistance of the new circuit increases as compared to the original circuit. Therefore, the current in the new circuit is reduced compared to that of the original circuit when steady-state conditions are established.*

OR

$\lvert\Delta V_2\rvert < \lvert\Delta V_1\rvert$*, because the inductor has nonnegligible resistance, and the total resistance of the new circuit increases as compared to the original circuit. Therefore, the potential difference across the inductor increases, which decreases the potential difference across* R_A *compared to that of the original circuit when steady-state conditions are established.*

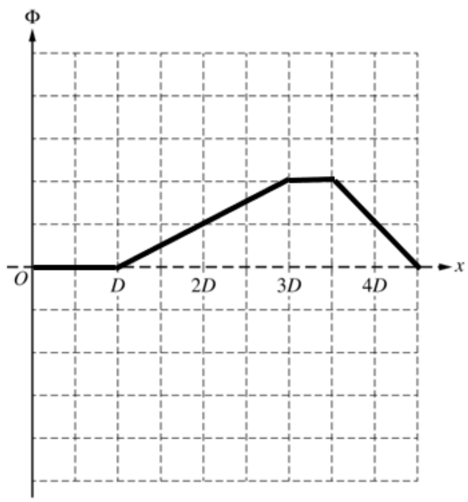
Total for part (d) 3 points

Total for question 2 15 points

Question 3: Free-Response Question — 15 points

(a)	For a sketch that indicates that the absolute value of the magnetic flux increases from zero at $x = D$ with a constant slope until $x = 2D$	**1 point**
	For a sketch that is continuous at $x = 2D$ and the absolute value of the magnetic flux increases until $x = 3D$ with the same slope as the slope in the region $D < x < 2D$	**1 point**
	For a sketch that indicates that the magnetic flux is constant and nonzero in the region $3D < x < 3.5D$	**1 point**
	For a sketch that indicates that the absolute value of the magnetic flux decreases from a nonzero value at $x = 3.5D$ to zero at $x = 4.5D$	**1 point**

Example Response



Scoring Note: A response that is reflected across the horizontal axis can earn the four points.
Scoring Note: The absolute values of the slopes in the entire regions $D < x < 3D$ and $3.5D < x < 4.5D$ are not considered for earning these points.

Total for part (a) — **4 points**

(b)(i)	For selecting Clockwise 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

Clockwise. 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 clockwise.

(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 Dv **1 point**

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

Example Response

$$\mathcal{E} = -B\frac{dA}{dt} = -BDv$$

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

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

Example Response

$$I_S = -\frac{BDv}{R}$$

Example Solution

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

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

$$\mathcal{E} = -\frac{d}{dt}(BA) = -\frac{d}{dt}(B(D)x) = -BD\frac{dx}{dt}$$

$$\mathcal{E} = -BDv$$

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

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

$$I_S = -\frac{BDv}{R}$$

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

Example Responses

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

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

Example Response

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

Example Solution

$$P = I^2R$$

$$P = \left(-\frac{BDv}{R}\right)^2 R$$

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

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 the same for both scenarios.
- The induced current occurs for the same amount of time for all transitions.
- The induced emf occurs for the same amount of time for all transitions

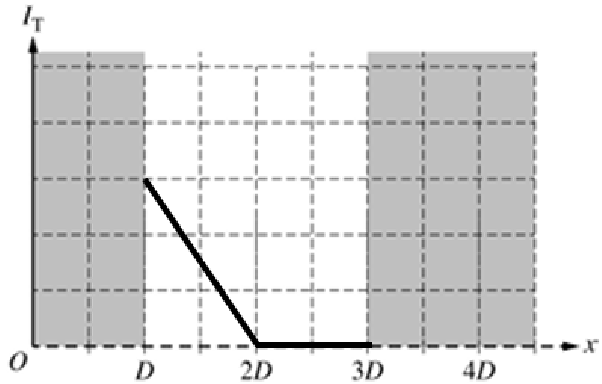
Example Response

The change in magnetic flux in the original scenario is the same as the new scenario, which produces an emf *and current that are the same in both scenarios. Therefore,* $E_{\text{new}} = E_{\text{original}}$

Total for part (c) 2 points

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

Example Response



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

Scoring Note: Any portion of the graph before $x = D$ and after $x = 3D$ will not be scored.

Total for part (d) 2 points

Total for question 3 15 points