Question 2: Translation Between Representations (TBR) — 12 points

A

For drawing a bar at $\frac{1}{4}T$ — **Point A1**

For drawing a bar at $\frac{1}{4}T$ that has a height of 3 units — **Point A2**

For indicating that $|\mathcal{E}|$ is zero at times $t = 0$ and $\frac{1}{2}T$ — **Point A3**

Example Response

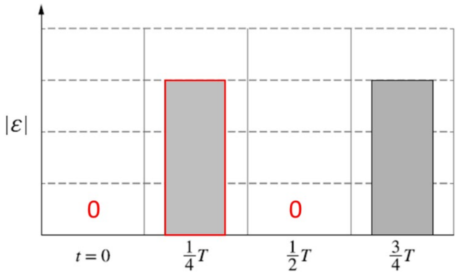


Figure 2

B

For a multistep derivation that includes the equation $\mathcal{E} = -\frac{d\Phi_B}{dt}$ — **Point B1**

Scoring Note: The negative sign does not have to be present in the expression for this point to be earned.

For a correct expression for the induced emf (e.g., $\mathcal{E} = BA\omega\sin(\omega t)$) — **Point B2**

For using Ohm's law to relate current and emf (e.g., $I = \frac{\mathcal{E}}{R}$) — **Point B3**

For a correct expression for the absolute value of the maximum induced current (e.g., $I = \frac{BA\omega}{R}$) — **Point B4**

Example Response

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

$$\mathcal{E} = -\frac{d}{dt}\left[BA\cos(\omega t)\right] = BA\omega\sin(\omega t)$$

$$\mathcal{E}_{max} = BA\omega$$

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

$$I_{max} = \frac{\mathcal{E}_{max}}{R} = \frac{BA\omega}{R}$$

C

For a curve that is approximately sinusoidal — **Point C1**

For a curve that shows exactly two cycles — **Point C2**

For a curve that starts at the origin and has equal maximum values and equal minimum values — **Point C3**

Scoring Note: A curve that starts and ends at $P = 0$ and has a single maximum can earn this point.

Example Response

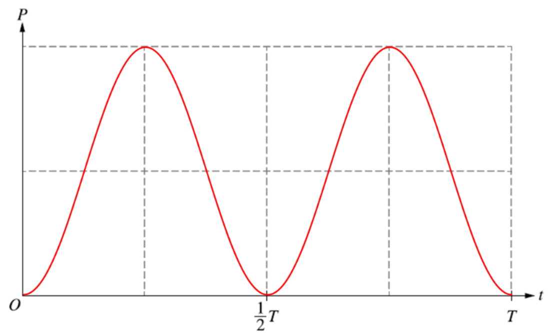


Figure 3

D

For correctly indicating whether the representations are consistent in parts A and C — **Point D1**

For a correct justification that indicates that the maxima and/or minima of the graph in part C align with the bars drawn in part A because P is proportional to $\mathcal{E}^2$ — **Point D2**

Example Response

Yes, part C is consistent with part A. P is proportional to $\mathcal{E}^2$. When $|\mathcal{E}|$ is maximum, P is maximum.

Question 3: Free-Response Question — 15 points

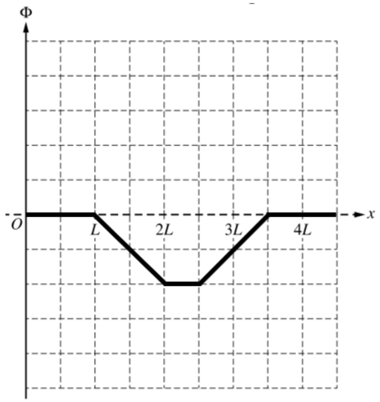
(a) For a sketch that indicates that the magnetic flux is zero from $x = 0$ to $x = L$ and for the region $x > 3.5L$ — **1 point**

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 — **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

$P = I^2R$ **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

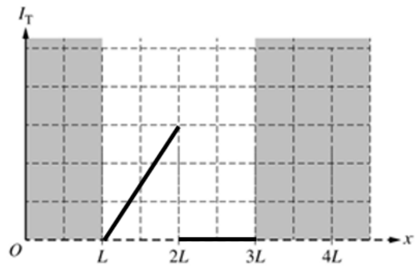
The change in magnetic flux is greater in the original scenario, which produces an emf *and current for a longer time. Therefore,* $E_{\text{new}} < E_{\text{original}}$.

Total for part (c) 2 points

(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

Question 3: Free-Response Question — 15 points

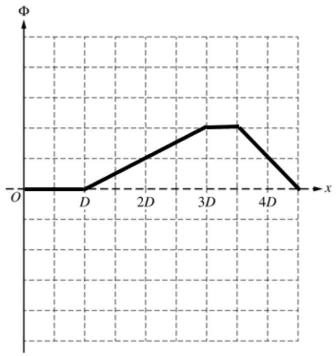
(a) For a sketch that indicates that the absolute value of the magnetic flux increases from zero at $x = D$ with a constant slope until $x = 2D$ — **1 point**

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 — **1 point**

OR

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

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.

AP Physics C: **Electricity and Magnetism: 2024 Set 2**

(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

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

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

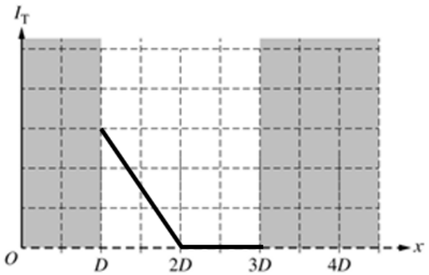
The change in magnetic flux in the original scenario is the same as the new scenario, which produces an emf *and current that are the same in both scenarios. Therefore,* $E_{\text{new}} = E_{\text{original}}$

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**

Question 3: Free-Response Question — 15 points

(a) For a loop rule expression that includes terms for the equivalent resistance $\frac{R}{2}$ and the potential difference across the battery — **1 point**

For an expression that includes charge Q in the term relating the potential difference across the capacitor and includes charge per unit time $\frac{dQ}{dt}$ in the term relating the potential difference across the pair of resistors — **1 point**

Example Response

$$\mathcal{E} - \Delta V_C - \Delta V_{R,eq} = 0$$

$$\mathcal{E} - \frac{Q}{C} - \frac{R}{2}\frac{dQ}{dt} = 0$$

Total for part (a) — **2 points**

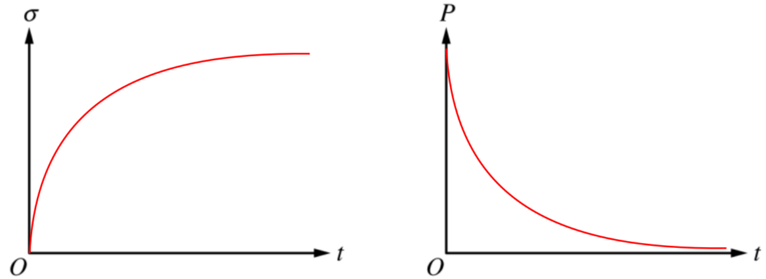
(b) For sketching a concave down and increasing curve on the graph σ as a function of t — **1 point**

For sketching a curve that is concave up and decreasing on the graph of P as a function of t — **1 point**

For sketching both curves that approach a slope of zero as time increases — **1 point**

Scoring Note: The third point can be earned even if the first two points are not earned.

Example Response



Total for part (b) — **3 points**

(c)(i) For a correct justification that could include one of the following: **1 point**

- An indication that the current is to the right with a justification that includes a statement that indicates that positive charge has accumulated on the top plate of Capacitor 1 and/or negative charge has accumulated on the bottom plate of Capacitor 1 when the switch was closed to Position A
- An indication that the current is to the right with a justification that includes a statement that indicates that the value of the electric potential of the top plate of Capacitor 1 is larger than the electric potential of the bottom plate of Capacitor 1 when the switch was closed to Position A

Example Responses

The current is directed towards the right because the top plate of Capacitor 1 is positively charged, meaning conventional current will flow clockwise.

OR

Toward the right. Current flows from high to low potential so it will flow from the top plate up and right through the switch.

(c)(ii) For indicating that the total charge on the positive plate of Capacitor 2 is $\frac{2}{3}Q_0$ **1 point**

Scoring Note: This point can be earned without supporting calculations.

Example Response

The potential difference across Capacitor 1 is equal to the potential difference across Capacitor 2. Capacitor 2 has twice the capacitance of Capacitor 1. Therefore, Capacitor 2 stores twice the charge that is stored on Capacitor 1. Due to conservation of charge, Capacitor 2 stores an amount of charge equal to $\frac{2}{3}Q_0$.

AP Physics C: **Electricity and Magnetism: 2023 Set 1**

(c)(iii) For an indication that the total energy dissipated by the resistors is the difference between an initial electric potential energy stored in one or both capacitors at time $t = t_1$ and a final electric potential energy stored on one or both capacitors after the new steady state conditions have been reached **1 point**

Example Response

$$E_R = U_C - U_{0C}$$

For indicating that only Capacitor 1 stores nonzero electric potential energy initially and both capacitors store nonzero electric potential energy after the new steady state conditions have been reached, or alternative consistent with part (c)(ii) **1 point**

Example Response

$$U_{0C} = U_{01}$$
$$U_C = U_1 + U_2$$

For correct substitutions for the charges stored on the capacitors after the new steady state conditions have been reached consistent with part (c)(ii) **1 point**

Example Response

$$\Delta E_R = U_C - U_{0C}$$
$$\Delta E_R = \left(\frac{1}{2}\left(\frac{1}{C}\right)\left(\frac{Q_0}{3}\right)^2 + \frac{1}{2}\left(\frac{1}{2C}\right)\left(\frac{2Q_0}{3}\right)^2\right) - \frac{1}{2}\frac{Q_0^2}{C}$$

Example Solution

$$\Delta E_R = U_C - U_{0C}$$
$$\Delta E_R = \left(\frac{1}{2}\left(\frac{1}{C}\right)\left(\frac{Q_0}{3}\right)^2 + \frac{1}{2}\left(\frac{1}{2C}\right)\left(\frac{2Q_0}{3}\right)^2\right) - \frac{1}{2}\frac{Q_0^2}{C}$$
$$\Delta E_R = \frac{Q_0^2}{6C} - \frac{1}{2}\frac{Q_0^2}{C}$$
$$\Delta E_R = -\frac{Q_0^2}{3C}$$

Total for part (c) 5 points

(d)	For indicating that the potential difference across each capacitor is the same or that the charge stored on each capacitor in steady state is the same	**1 point**
	Example Responses $\Delta V_1 = \Delta V_2$ **OR** $Q_1 = Q_2$	
	For recognizing that the capacitance of each capacitor is now the same in the new configuration	**1 point**
	Example Response *After steady state conditions are reached, both capacitors have the same potential difference. The new capacitance of Capacitor 2 is equal to the capacitance of Capacitor 1 because the capacitance of a capacitor is inversely related to the distance between the plates of a capacitor. Therefore, since* $U_C = \frac{1}{2}C(\Delta V)^2$, $\frac{U_2}{U_1} = 1$.	
	Total for part (d)	**2 points**
(e)(i)	For a loop rule that includes the terms for the emf of the battery, the potential difference across the pair of resistors, and the potential difference across Capacitor 1	**1 point**
	Example Response $\mathcal{E} - \Delta V_R - \Delta V_C = 0$	
	For a correct answer	**1 point**
	Example Response $I = \frac{Q_0}{RC}$	
	Example Solution $\mathcal{E} - \Delta V_R - \Delta V_C = 0$ $\mathcal{E} - I\left(\frac{R}{2}\right) - \left(\frac{Q_0}{2C}\right) = 0$ $\frac{Q_0}{C} - I\left(\frac{R}{2}\right) - \left(\frac{Q_0}{2C}\right) = 0$ $\frac{Q_0}{2C} - I\left(\frac{R}{2}\right) = 0$ $\frac{Q_0}{2C} = I\left(\frac{R}{2}\right)$ $\frac{Q_0}{C} = IR$ $I = \frac{Q_0}{RC}$	
(e)(ii)	For indicating that the current is zero	**1 point**
	Total for part (e)	**3 points**
	Total for question 3	**15 points**

Question 3: Free-Response Question — 15 points

(a)	For selecting "Counterclockwise" and an attempt at a relevant justification	**1 point**
	For a justification that correctly relates how the changing current in the solenoid changes the flux through the loop with respect to time	**1 point**
	For a justification that has a correct relationship between the change in magnetic flux through the loop of wire and how the current in the loop changes to oppose the change in magnetic flux	**1 point**
	Example Response *In the end view, the magnetic field due to the solenoid is directed into the page. The current in the solenoid is increasing; thus, the magnetic flux is increasing. According to Lenz's law, because the magnetic flux is increasing and into the page, the current in the loop must create a magnetic field directed out of the page; thus, the current in the loop must be counterclockwise the counter the change in magnetic flux.*	
	Total for part (a)	**3 points**
(b)	For using an appropriate equation to calculate emf in the loop	**1 point**
	Example Response $\varepsilon = \left\lvert\frac{d\Phi}{dt}\right\rvert = \frac{d(BA)}{dt} = A\frac{dB}{dt}$	
	For correctly substituting the magnetic field for a solenoid into above equation	**1 point**
	Example Response $\varepsilon = A\frac{d(\mu_0 nI)}{dt} = \mu_0 nA\frac{dI}{dt}$	
	For using Ohm's law to calculate the current in the loop	**1 point**
	Example Response $I_{\text{loop}} = \frac{\varepsilon}{R} = \frac{\mu_0 nA}{R}\frac{dI}{dt}$	
	For correctly substituting into the previous equation for the induced current in the loop	**1 point**
	Example Response $I_{\text{loop}} = \frac{\left(4\pi \times 10^{-7}\ \text{T•m/A}\right)\left(\frac{500\ \text{turns}}{0.25\ \text{m}}\right)\left((\pi)(0.10\ \text{m})^2\right)}{(3\ \Omega)}(5.0\ \text{A/s}) = 1.3 \times 10^{-4}\ \text{A}$	
	Total for part (b)	**4 points**

(c)	For using an appropriate expression for the power for a constant current through a resistor **Example Response** $P = I_{\text{loop}}{}^2 R$	**1 point**
	For a correct substitution consistent with (b) into a correct expression for electrical power **Example Response** $P = I_{\text{loop}}{}^2 R = \left(\frac{\mu_0 nA}{R}\frac{dI}{dt}\right)^2 R = \left(1.3\times10^{-4}\ \text{A}\right)^2(3.0\ \Omega) = 5.2\times10^{-8}\ \text{W}$	**1 point**
	For correctly substituting the power dissipated by the loop of wire into a correct energy equation **Example Response** $P = \frac{dE}{dt} = \frac{\Delta E}{\Delta t} \therefore \Delta E = P\Delta t$ $\Delta E = \left(5.2\times10^{-8} W\right)(2.0\ \text{s}) = 1.0\times10^{-7}\ \text{J}$	**1 point**
	Total for part (c)	**3 points**
(d)	For selecting "The plane of the loop is not perpendicular to the axis of the solenoid."	**1 point**
	For correctly justifying the selection **Scoring Note:** A response cannot earn this point if the incorrect selection is chosen.	**1 point**
	Example Response *If the plane of the loop is not perpendicular to the axis of the solenoid it is not perpendicular to the magnetic field. Therefore, the magnetic flux and emf will be less, so the current will be less.*	
	Total for part (d)	**2 points**
(e)	For selecting "$\frac{I_2}{I_1} = 2$" with an attempt at a relevant justification **Scoring Note:** The response can earn this point if selecting "$\frac{I_2}{I_1} > 2$" and only referencing the increase in flux through the loop in the justification.	**1 point**
	For a statement that indicates that the resistance of the second loop is double the resistance of the original loop	**1 point**
	For a statement that indicates that the new emf is four times greater than the original emf due to the increased flux through the loop resulting from the quadrupled area	**1 point**

Example Response

The magnetic flux quadruples. This is because of the increase in area of the loop, which quadruples the emf. The resistance of the loop doubles because the length of the wire doubles. Therefore, $\frac{I_2}{I_1} = 2$.

$$\varepsilon = \mu_0 n\left(A_{loop}\right) = \mu_0 n\left(\pi r^2\right)\frac{dI}{dt}$$

The radius of the loop doubles. Therefore, the area of the loop quadruples.

$$R = \rho\frac{2\pi r}{A_{wire}}$$

The radius of the loop doubles. Therefore, the resistance of the loop doubles.

$$\frac{I_2 = \frac{\varepsilon}{R} = \frac{\mu_0 n(4)A}{(2)R}\frac{dI}{dt}}{I_1 = \frac{\varepsilon}{R} = \frac{\mu_0 nA}{R}\frac{dI}{dt}} = 2$$

Total for part (e) 3 points

Total for question 3 15 points

Question 3: Free-Response Question — 15 points

(a) For using Faraday's law to relate emf to change in flux — **1 point**

$$\mathcal{E} = \left|\frac{d\Phi}{dt}\right| = \left|\frac{d(B \cdot A)}{dt}\right|$$

For a correct expression for the emf — **1 point**

$$\mathcal{E} = \left|A\frac{dB}{dt}\right| = \left|A\frac{d}{dt}\left(\frac{\beta}{t}\right)\right| = \left|-\frac{A\beta}{t^2}\right| = \frac{A\beta}{t^2}$$

For correctly substituting into Ohm's law — **1 point**

$$I = \frac{\Delta V}{R} = \frac{\mathcal{E}}{R} = \frac{A\beta}{Rt^2}$$

Scoring note: Full credit is earned if the negative sign is included.

Total for part (a) — 3 points

(b) For using a correct equation to calculate the energy dissipated in the ring — **1 point**

$$E = \int P dt = \int I^2 R dt$$

For correctly substituting into the equation above — **1 point**

$$E = \int\left(\frac{A\beta}{Rt^2}\right)^2 R dt = \int \frac{A^2\beta^2}{R^2 t^4} R dt$$

For indicating the correct limits or constant of integration — **1 point**

$$E = \frac{A^2\beta^2}{R}\int_1^2 \frac{1}{t^4} dt$$

For a correct answer with units — **1 point**

$$E = \frac{A^2\beta^2}{R}\left[-\frac{1}{3t^3}\right]_1^2 = \frac{\left(0.50\text{ m}^2\right)^2(0.50\text{ T}\cdot\text{s})^2}{(3)(2.00\ \Omega)}\left(-\frac{1}{2^3}-\left(-\frac{1}{1^3}\right)\right) = 0.0091\text{ J}$$

Total for part (b) — 4 points

(c) For selecting "Less than" and attempting a relevant justification — **1 point**

For a correct justification — **1 point**

Example response for part (c)

After the ring rotates, fewer magnetic field lines pass through the ring, and the flux is less than before. Thus, the emf, current, and rate at which energy is dissipated is less.

Total for part (c) — 2 points

(d) For using a correct equation to calculate angular speed — **1 point**

$$\omega = \frac{2\pi}{T}$$

For substituting appropriate values from the graph in the correct equation — **1 point**

$$\omega = \frac{(2\pi)}{(2\text{ s})} = 3.14\ \frac{\text{rad}}{\text{s}}$$

Total for part (d) — 2 points

(e) For using a correct equation for solving for the emf in terms of the angular speed — **1 point**

$$\mathcal{E} = \frac{d\Phi}{dt} = \frac{d(B \cdot A)}{dt} = BA\frac{d}{dt}(\cos(\omega t)) = -BA\omega\sin(\omega t)$$

For correctly substituting into the correct equation — **1 point**

$$\mathcal{E}_{\text{MAX}} = BA\omega = (0.50\text{ T})\left(0.50\text{ m}^2\right)\left(3.14\ \frac{\text{rad}}{\text{s}}\right) = 0.79\text{ V}$$

Total for part (e) — 2 points

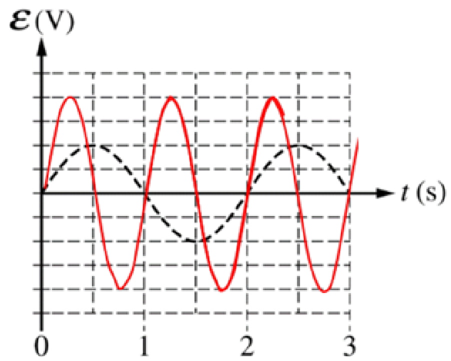
(f) For a sine curve with half the period of the dashed curve and a correct justification — **1 point**

For a sine curve with twice the amplitude of the dashed curve and a correct justification — **1 point**

OR

a sine curve with an amplitude consistent with work shown in part (e)

Example response for part (f)



Because the rotational speed is twice the original speed, then, according to the equation $|\mathcal{E}| = B_0 A\omega\sin(\omega t)$ this will double the amplitude of the curve and cut the period in half.

Total for part (f) — 2 points

Total for question 3 — 15 points

2019

AP® CollegeBoard

AP® Physics C: Electricity and Magnetism

Scoring Guidelines Set 1

2019 SCORING GUIDELINES

General Notes About 2019 AP Physics Scoring Guidelines

1. The solutions contain the most common method of solving the free-response questions and the allocation of points for this solution. Some also contain a common alternate solution. Other methods of solution also receive appropriate credit for correct work.

2. The requirements that have been established for the paragraph-length response in Physics 1 and Physics 2 can be found on AP Central at https://secure-media.collegeboard.org/digitalServices/pdf/ap/paragraph-length-response.pdf.

3. Generally, double penalty for errors is avoided. For example, if an incorrect answer to part (a) is correctly substituted into an otherwise correct solution to part (b), full credit will usually be awarded. One exception to this may be cases when the numerical answer to a later part should be easily recognized as wrong, e.g., a speed faster than the speed of light in vacuum.

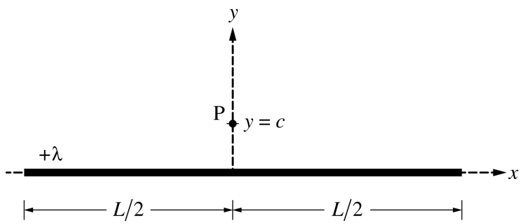
4. Implicit statements of concepts normally receive credit. For example, if use of the equation expressing a particular concept is worth 1 point, and a student's solution embeds the application of that equation to the problem in other work, the point is still awarded. However, when students are asked to derive an expression, it is normally expected that they will begin by writing one or more fundamental equations, such as those given on the exam equation sheet. For a description of the use of such terms as "derive" and "calculate" on the exams, and what is expected for each, see "The Free-Response Sections — Student Presentation" in the *AP Physics; Physics C: Mechanics, Physics C: Electricity and Magnetism Course Description* or "Terms Defined" in the *AP Physics 1: Algebra-Based Course and Exam Description* and the *AP Physics 2: Algebra-Based Course and Exam Description*.

5. The scoring guidelines typically show numerical results using the value $g = 9.8 \text{ m/s}^2$, but the use of 10 m/s^2 is of course also acceptable. Solutions usually show numerical answers using both values when they are significantly different.

6. Strict rules regarding significant digits are usually not applied to numerical answers. However, in some cases answers containing too many digits may be penalized. In general, two to four significant digits are acceptable. Numerical answers that differ from the published answer due to differences in rounding throughout the question typically receive full credit. Exceptions to these guidelines usually occur when rounding makes a difference in obtaining a reasonable answer. For example, suppose a solution requires subtracting two numbers that should have five significant figures and that differ starting with the fourth digit (e.g., 20.295 and 20.278). Rounding to three digits will lose the accuracy required to determine the difference in the numbers, and some credit may be lost.

Question 1

15 points



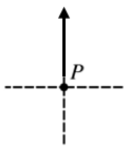
Note: Figure not drawn to scale.

A very long, thin, nonconducting cylinder of length L is centered on the y-axis, as shown above. The cylinder has a uniform linear charge density $+\lambda$. Point P is located on the y-axis at $y = c$, where $L >> c$.

(a)

i. LO CNV-3.B.a, SP 7.A
1 point

On the figure shown below, draw an arrow to indicate the direction of the electric field at point P due to the long cylinder. The arrow should start on and point away from the dot.



For drawing an arrow at point P that points upward		1 point

ii. LO CNV-2.F, SP 7.C
1 point

Describe the shape and location of a Gaussian surface that can be used to determine the electric field at point P due to the long cylinder.

For describing a Gaussian surface that could be used to determine the electric field at point P		1 point
Example: Drawing a cylinder that is coaxial with the thin cylinder and whose surface contains point P can be used to determine the electric field at point P.		
Note: Credit is earned if the student draws the correct surface on the figure.		

Question 1 (continued)

(a) continued

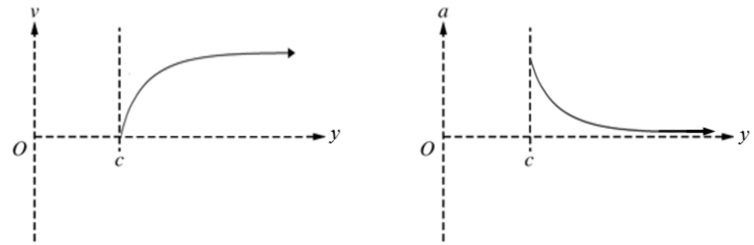
iii. LO CNV-2.C, SP 5.A, 5.E
3 points

Use your Gaussian surface to derive an expression for the magnitude of the electric field at point P. Express your answer in terms of λ, c, L, and physical constants, as appropriate.

For using Gauss's law to determine the electric field at point P		1 point
$\frac{q_{enc}}{\varepsilon_0} = \int E \bullet dA \therefore \frac{Q}{\varepsilon_0} = EA$		
For correctly substituting for the charge into the equation above		1 point
For correctly substituting for the area or into the equation above		1 point
$\frac{\lambda L}{\varepsilon_0} = E(2\pi cL) \therefore E = \frac{\lambda}{2\pi\varepsilon_0 c} = \frac{2k\lambda}{c}$		

(b) LO ACT-1.D, SP 3.C
2 points

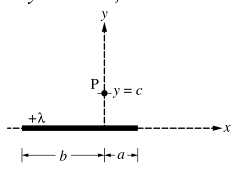
A proton is released from rest at point P. On the axes below, sketch the velocity v as a function of position y and the acceleration a as a function of position y for the proton.



For a concave down graph for v as a function of position x that does not start at the origin		1 point
For a concave up graph for a as a function of position x that has an asymptote at the horizontal axis		1 point

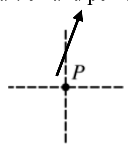
Question 1 (continued)

The original cylinder is now replaced with a much shorter thin, nonconducting cylinder with the same uniform linear charge density $+\lambda$, as shown in the figure below. The length of the cylinder to the right of the y-axis is a, and the length of the cylinder to the left of the y-axis is b, where $a < b$.



(c) LO CNV-3.B.a, SP 7.A
2 points

On the figure shown below, draw an arrow to indicate the direction of the electric field at point P due to the shorter cylinder. The arrow should start on and point away from the dot.



For drawing an arrow at point P that points to the right		1 point
For drawing an arrow at point P that points up and to the right		1 point

(d)
i. and ii. LO CNV-2.F, SP 7.A
1 point

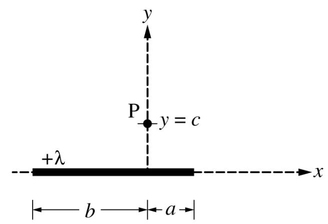
Is there a single Gaussian surface that can be used with Gauss's law to derive an expression for the electric field at point P?

____ Yes ____ No

If your answer to part (d)(i) is yes, explain how you can use Gauss's law to derive an expression for the field at point P. If your answer to part (d)(i) is no, explain why Gauss's law cannot be applied to derive an expression for the electric field in this case.

For selecting "No" with a valid explanation		1 point
Claim: Select "No." Evidence: The length of the cylinder is not much greater than the distance from the cylinder to point P and the charge distribution is asymmetric. Reasoning: Therefore, cannot use the approximation of the constant magnitude of electric field over a cylindrical surface.		

Question 1 (continued)



Note: This figure is shown again for reference.

A student in class argues that using the integral shown below might be a useful approach for determining the electric field at point P.

$$E = \int \frac{1}{4\pi\varepsilon_0} \frac{1}{r^2}\, dq$$

The student uses this approach and writes the following two integrals for the magnitude of the horizontal and vertical components of the electric field at point P.

$$\text{Horizontal component: } |E_x| = \frac{\lambda}{4\pi\varepsilon_0} \int_{-b}^{a} \frac{x}{\left(c^2 + x^2\right)^{3/2}}\, dx$$

$$\text{Vertical component: } |E_y| = \frac{\lambda}{4\pi\varepsilon_0} \int_{-b}^{a} \frac{y}{\left(c^2 + x^2\right)}\, dy$$

(e)
i. LO CNV-3.A, SP 7.A
1 point

One of the two expressions above is not correct. Which expression is not correct?

____ Horizontal component ____ Vertical component

For correctly selecting "Vertical component"		1 point

Question 1 (continued)

(e) continued

ii. LO CNV-3.A, SP 7.D
4 points

Identify two mistakes in the incorrect expression, and explain how to correct the mistakes.

For indicating the integral is not along the length of the cylinder		1 point
For an appropriate correction		1 point
Claim: Change *dy* to *dx*. Evidence: The integral is not along the cylinder. Reasoning: This change will make the integral valid.		
For indicating the power on the denominator term for the vertical component is incorrect		1 point
For an appropriate correction		1 point
Claim: The power on the term in the denominator should be $3/2$. Evidence: The units of the integrand are not valid. Reasoning: This change will make the integrand valid.		

Learning Objectives

ACT-1.D: Determine the motion of a charged object of specified charge and mass under the influence of an electrostatic force.
CNV-2.C: State and use Gauss's law in integral form to derive unknown electric fields for planar, spherical, or cylindrically symmetrical charge distributions.
CNV-2.F: Describe the general features of an unknown charge distribution, given other features of the system.
CNV-3.A: Derive expressions for the electric field of specified charge distributions using integration and the principle of superposition. Examples of such charge distributions include a uniformly charged wire, a thin ring of charge (along the axis of the ring), and a semicircular or part of a semicircular arc.
CNV-3.B.a: Identify and qualitatively describe situations in which the direction and magnitude of the electric field can be deduced from symmetry considerations and understanding the general behavior of certain charge distributions.

Science Practices

3.C: Sketch a graph that shows a functional relationship between two quantities.
5.A: Select an appropriate law, definition, or mathematical relationship or model to describe a physical situation.
5.E: Derive a symbolic expression from known quantities by selecting and following a logical algebraic pathway.
7.A: Make a scientific claim.
7.C: Support a claim with evidence from physical representations.
7.D: Provide reasoning to justify a claim using physical principles or laws.

Question 2

15 points

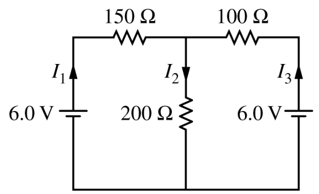


Figure 1

The circuit shown above is constructed with two 6.0 V batteries and three resistors with the values shown. The currents I_1, I_2, and I_3 in each branch of the circuit are indicated.

(a)

i. LO CNV-6.F.b, SP 6.A
3 points

Using Kirchhoff's rules, write, but DO NOT SOLVE, equations that can be used to solve for the current in each resistor.

For an equation representing the sum of the currents at one of the junctions		1 point
$I_1 - I_2 + I_3 = 0$		
For an equation representing the sum of the potential differences around one of the loops		1 point
For an equation representing the sum of the potential differences around a loop different from the above loop		1 point
$6 - 150I_1 - 200I_2 = 0$		
$6 - 100I_3 - 200I_2 = 0$		
$6 - 150I_1 + 100I_3 - 6 = 0$		
Note: Full credit is earned for two correct loop equations using loop currents.		

ii. LO CNV-6.F.b, SP 6.C
2 points

Calculate the current in the $200\ \Omega$ resistor.

For combining the equations from part (a)(i)		1 point
$I_1 - I_2 + I_3 = 0$ $-I_1 - 1.33I_2 = -.04 \therefore -4.33I_2 = -0.10$ $-I_3 - 2I_2 = -.06$		
Note: Credit is earned if students indicate they used a calculator function to solve the system of equations.		
For a correct answer with correct units		1 point
$-4.33I_2 = -0.10 \therefore I_2 = 0.023\text{ A}$		

Question 2 (continued)

(a) continued
iii. LO CNV-5.A.a, SP 6.C
1 point

Calculate the power dissipated by the $200\ \Omega$ resistor.

For using a correct equation to calculate the power in the $200\ \Omega$ resistor		1 point
$P = I^2R = (0.023\text{ A})^2(200\ \Omega)\ \therefore\ P = 0.107\text{ W}$		

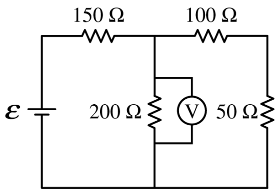


Figure 2

The two 6.0 V batteries are replaced with a battery with voltage $\mathcal{E}$ and a resistor of resistance $50\ \Omega$, as shown above. The voltmeter V shows that the voltage across the $200\ \Omega$ resistor is 4.4 V.

(b) LO CNV-6.C.a, SP 6.B, 6.C
2 points

Calculate the current through the $50\ \Omega$ resistor.

For correctly calculating the equivalent resistance of the branch with the $50\ \Omega$ resistor		1 point
$R = 100\ \Omega + 50\ \Omega = 150\ \Omega$		
For using the correct potential difference in Ohm's law to calculate the current in the $50\ \Omega$ resistor		1 point
$I = \dfrac{V}{R} = \dfrac{(4.4\text{ V})}{(100\ \Omega + 50\ \Omega)}\ \therefore\ I = 0.029\text{ A}$		

Question 2 (continued)

(c) LO CNV-6.C.a, SP 6.A, 6.C
3 points

Calculate the voltage $\mathcal{E}$ of the battery.

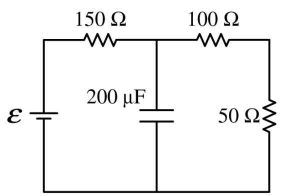
For using a correct equation to determine the current through the $150\ \Omega$ resistor		1 point
For correctly substituting the current from part (b) as I_3		1 point
$I_1 = I_2 + I_3 = \dfrac{(4.4\text{ V})}{(200\ \Omega)} + 0.029\text{ A} = 0.051\text{ A}$		
For using a correct equation to determine the emf of the battery		1 point
$\mathcal{E} = I_1R_1 + V_2 = (0.051\text{ A})(150\ \Omega) + 4.4\text{ V} = 12.1\text{ V}$		
Alternate Third Point		
For calculating the equivalent resistance of the circuit and substituting this resistance into a correct equation to determine the emf of the battery		*1 point*
$R_T = 150\ \Omega + \dfrac{1}{\dfrac{1}{200\ \Omega} + \dfrac{1}{150\ \Omega}} = 236\ \Omega$		
$\mathcal{E} = I_1R_T = (0.051\text{ A})(236\ \Omega) = 12.0\text{ V}$		
Alternate Solution		*Alternate Points*
For using a correct equation to determine the equivalent resistance of the parallel resistors		*1 point*
$\dfrac{1}{R_P} = \dfrac{1}{200\ \Omega} + \dfrac{1}{150\ \Omega}\ \therefore\ R_P = 86\ \Omega$		
For correctly substituting the given potential difference and the calculated equivalent resistance to determine the total current of the circuit		*1 point*
$I_T = \dfrac{(4.4\text{ V})}{(86\ \Omega)} = 0.051\text{ A}$		
For calculating the equivalent resistance of the circuit and substituting into a correct equation to determine the emf of the battery		*1 point*
$R_T = 150\ \Omega + 86\ \Omega = 236\ \Omega$		
$\mathcal{E} = I_1R_T = (0.051\text{ A})(236\ \Omega) = 12.0\text{ V}$		

Question 2 (continued)

(d)

i. LO CNV-7.B.a, SP 6.A, 6.C
2 points

The $200\ \Omega$ resistor in the circuit in Figure 2 is replaced with a $200\ \mu F$ capacitor, as shown on the right, and the circuit is allowed to reach steady state. Calculate the current through the $50\ \Omega$ resistor.



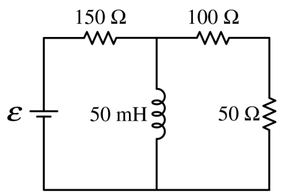
For substituting the voltage consistent with part (c) into Ohm’s law		1 point
For correctly calculating the equivalent resistance of the circuit		1 point
$I = \dfrac{\mathcal{E}}{R_{tot}} = \dfrac{(12.1\ \text{V})}{(150\ \Omega + 100\ \Omega + 50\ \Omega)} = 40.3\ \text{mA}$		

ii. LO CNV-10.C.a, SP 7.A, 7.C
2 points

The $200\ \Omega$ resistor in the circuit in Figure 2 is replaced with an ideal 50 mH inductor, as shown on the right, and the circuit is allowed to reach steady state. Is the current in the $50\ \Omega$ resistor greater than, less than, or equal to the current calculated in part (b)?

____ Greater than ____ Less than ____ Equal to

Justify your answer.



For correctly selecting “Less than” with an attempt at a relevant justification		1 point
For a correct justification		1 point
Example: Because steady state is reached, the inductor will act as a short circuit. So all the current will pass through the inductor and no current will pass through the $50\ \Omega$ resistor.		

Question 2 (continued)

Learning Objectives

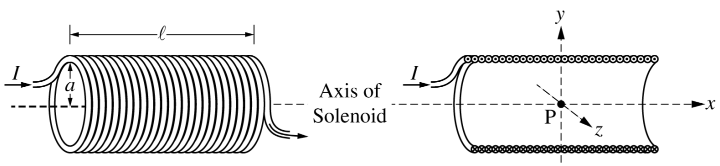
CNV-5.A.a: Derive expressions that relate current, voltage, and resistance to the rate at which heat is produced in a resistor.
CNV-6.C.a: Calculate voltage, current, and power dissipation for any resistor in a circuit containing a network of known resistors with a single battery or energy source.
CNV-6.F.b: Set up simultaneous equations to calculate at least two unknowns (currents or resistance values) in a multi-loop circuit.
CNV-7.B.a: Calculate the potential difference across a capacitor in a circuit arrangement containing capacitors, resistors, and an energy source under steady-state conditions.
CNV-10.C.a: Calculate initial transient currents and final steady-state currents through any part of a series or parallel circuit containing an inductor and one or more resistors.

Science Practices

6.A: Extract quantities from narratives or mathematical relationships to solve problems.
6.B: Apply an appropriate law, definition, or mathematical relationship to solve a problem.
6.C: Calculate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.
7.A: Make a scientific claim.
7.C: Support a claim with evidence from physical representations.

Question 3

15 points



Solenoid — Cutaway View

Note: Figures not drawn to scale.

A solenoid is used to generate a magnetic field. The solenoid has an inner radius a, length ℓ, and N total turns of wire. A power supply, not shown, is connected to the solenoid and generates current I, as shown in the figure on the left above. The x-axis runs along the axis of the solenoid. Point P is in the middle of the solenoid at the origin of the xyz-coordinate system, as shown in the cutaway view on the right above. Assume $\ell >> a$.

(a) LO CNV-8.E.a, SP 7.A, 7.C
2 points

Select the correct direction of the magnetic field at point P.

____ $+x$-direction ____ $+y$-direction ____ $+z$-direction
____ $-x$-direction ____ $-y$-direction ____ $-z$-direction

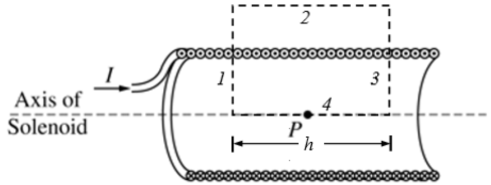
Justify your selection.

For choosing the "$+x$-direction" and providing a justification		1 point
For a correct justification		1 point
Example: Using the right-hand rule for current on the left side of the solenoid, the fingers curl into the loop, so the magnetic field points to the right, or in the $+x$-direction.		
Example: Using the right-hand rule for solenoids, when the fingers curl around the solenoid in the direction of the current, the thumb points to the right, therefore the magnetic field is to the right, or in the $+x$-direction.		

Question 3 (continued)

(b)
i. LO CNV-8.C.c, SP 3.D
1 point

On the cutaway view below, clearly draw an Amperian loop that can be used to determine the magnetic field at point P at the center of the solenoid.



For drawing a rectangle with one side along the central axis of the solenoid and another side outside the solenoid and whose edges do not extend beyond the solenoid		1 point

ii. LO CNV-8.C.c, SP 5.A, 5.E
2 points

Use Ampere's law to derive an expression for the magnetic field strength at point P. Express your answer in terms of I, ℓ, N, a, and physical constants, as appropriate.

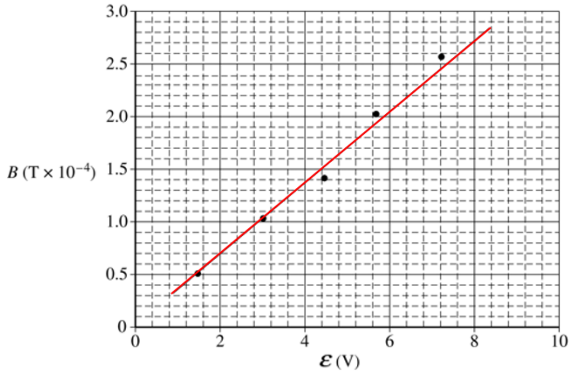
For using Ampere's law to calculate the magnetic field along the axis of the solenoid		1 point
$\int B \bullet d\ell = \mu_0 I_{enc} \therefore \left(\int B \bullet d\ell\right)_1 + \left(\int B \bullet d\ell\right)_2 + \left(\int B \bullet d\ell\right)_3 + \left(\int B \bullet d\ell\right)_4 = \mu_0 I_{enc}$		
$\left(\int B \bullet d\ell\right)_1 + 0 + \left(-\left(\int B \bullet d\ell\right)_1\right) + Bh = \mu_0 \frac{N}{\ell} hI$		
$Bh = \mu_0 \frac{N}{\ell} hI$		
For a correct answer		1 point
$B = \frac{\mu_0 NI}{\ell}$		

Some physics students conduct an experiment to determine the resistance R_S of a solenoid with radius $a = 0.015$ m, total turns $N = 100$, and total length $\ell = 0.40$ m. The students connect the solenoid to a variable power supply. A magnetic field sensor is used to measure the magnetic field strength along the central axis at the center of the solenoid. The plot of the magnetic field strength B as a function of the emf $\mathcal{E}$ of the power supply is shown below.

Question 3 (continued)

(c) i. LO CNV-8.C.c, SP 4.C
1 point

On the graph above, draw a best-fit line for the data.



For drawing a best-fit line with at least one point above and one point below the line		1 point

ii. LO CNV-8.C.c, SP 6.B, 6.C
2 points

Use the straight line to determine the resistance R_S of the solenoid used in the experiment.

For calculating the slope using the best-fit line and not the data points unless they fall on the best-fit line		1 point
$slope = \dfrac{\Delta y}{\Delta x} = \dfrac{(2.5 - 0.9)\left(\times 10^{-4}\ \text{T}\right)}{(6.4 - 2.0)\ \text{V}} = 0.36 \times 10^{-4} = 3.6 \times 10^{-5}\ \text{T/V}$		
For correctly giving the expression that relates the slope to the resistance of the solenoid		1 point
$B = \dfrac{\mu_0 NI}{\ell} = \dfrac{\mu_0 N \mathcal{E}}{\ell R} \therefore slope = \dfrac{\mu_0 N}{\ell R_S} \therefore R_S = \dfrac{\mu_0 N}{\ell \times slope}$ $R_S = \dfrac{\left(4\pi \times 10^{-7}\ (\text{T}\cdot\text{m})/\text{A}\right)(100\ \text{turns})}{(0.40\ \text{m})\left(3.6 \times 10^{-5}\ \text{T/V}\right)} = 8.7\ \Omega$		

One of the students notes that the horizontal component of the magnetic field of Earth is 2.5×10^{-5} T.

Question 3 (continued)

(d)
i. LO CNV-8.E.a, SP 2.D
1 point

Is there evidence from the graph that the horizontal orientation of the solenoid affects the measured values for B?

____ Yes ____ No

Justify your answer.

If the line on the graph does not go through the origin, select "Yes"		
For a correct justification		1 point
Example: The horizontal component of Earth's magnetic field will add or subtract from the magnetic field of the solenoid depending on the orientation of the solenoid.		
Alternate Solution		*Alternate Points*
If the line on the graph does pass through the origin, select "No"		
For a correct justification		*1 point*
Example: Based on the graph, the line passes through the origin, so the magnetic field is zero when the emf of the power supply is zero, therefore Earth's magnetic field is not affecting the values of B.		

ii. LO CNV-8.E.a, SP 2.E
1 point

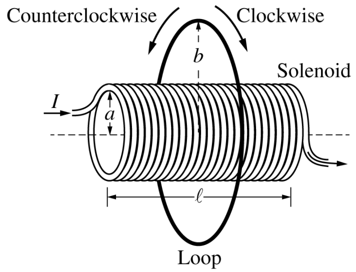
Would the horizontal orientation of the solenoid affect the calculated value for R_S ?

____ Yes ____ No

Justify your answer.

Select "No"		
For a correct justification		1 point
Example: The horizontal component of Earth's magnetic field will not affect the change in magnetic field as the emf is changed. Therefore, the value for the resistance of the solenoid will not change.		

Question 3 (continued)



A thin conducting loop of radius b and resistance R_L is placed concentric with the solenoid, as shown above. The current in the solenoid is decreased from I to zero over time Δt.

(e)

i. LO FIE-6.A.b, SP 7.A, 7.C
2 points

Is the direction of the induced current in the loop clockwise or counterclockwise during the time period that the current in the solenoid is decreasing?

____ Clockwise ____ Counterclockwise

Justify your answer.

Select "Clockwise"		
For a justification indicating that the magnetic field inside the solenoid, and therefore the loop, will decrease		1 point
For a justification using Lenz's law to relate the change in magnetic field to the direction of the current		1 point
Example: As the current in the solenoid decreases, the magnetic field inside the solenoid decreases. As the solenoid's magnetic field decreases, the induced current in the loop will create a magnetic field to oppose this change. Because the solenoid's magnetic field is toward the right and decreasing, the magnetic field due to the current in the loop must be toward the right. Therefore, the current in the loop must be clockwise.		

Question 3 (continued)

(e) continued

ii. LO FIE-6.A.d, SP 5.A, 5.E
3 points

Derive an equation for the average induced current i_{IND} in the loop during the time period that the current in the solenoid is decreasing. Express your answer in terms of I, ℓ, N, a, b, R_L, R_S, Δt, and physical constants, as appropriate.

For using Faraday's law to calculate the emf in the loop		1 point
$\varepsilon = \left\lvert \frac{d\Phi}{dt} \right\rvert = \frac{d(BA)}{dt} = A\frac{\Delta B}{\Delta t}$		
For using Ohm's law to calculate the current in the loop		1 point
$I_{IND} = \frac{V}{R} = \frac{A\Delta B/\Delta t}{R_L} = \frac{A\Delta B}{R_L \Delta t}$		
For using the correct radius for the area in the equation above		1 point
$I_{IND} = \frac{\pi a^2 \mu_0 N \Delta I/\ell}{R_L \Delta t} = \frac{\pi a^2 \mu_0 N I}{R_L \ell \Delta t}$		

Learning Objectives

CNV-8.C.c: Derive the expression for the magnetic field of an ideal solenoid (length dimension is much larger than the radius of the solenoid) using Ampère's law.
CNV-8.E.a: Describe the direction of a magnetic field at a point in space due to various combinations of conductors, wires, cylindrical conductors, or loops.
FIE-6.A.b: Describe the direction of an induced current in a conductive loop that is placed in a changing magnetic field.
FIE-6.A.d: Calculate the magnitude and direction of induced EMF and induced current in a conductive loop (or conductive bar) when the magnitude of either the field or area of loop is changing at a constant rate.

Science Practices

2.D: Make observations or collect data from representations of laboratory setups or results.
2.E: Identify or describe potential sources of experimental error.
3.D: Create appropriate diagrams to represent physical situations.
4.C: Linearize data and/or determine a best-fit line or curve.
5.A: Select an appropriate law, definition, or mathematical relationship or model to describe a physical situation.
5.E: Derive a symbolic expression from known quantities by selecting and following a logical algebraic pathway.
6.B: Apply an appropriate law, definition, or mathematical relationship to solve a problem.
6.C: Calculate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.
7.A: Make a scientific claim.
7.C: Support a claim with evidence from physical representations.

2017

AP Physics C: Electricity and Magnetism

Scoring Guidelines

AP® PHYSICS
2017 SCORING GUIDELINES

General Notes About 2017 AP Physics Scoring Guidelines

1. The solutions contain the most common method of solving the free-response questions and the allocation of points for this solution. Some also contain a common alternate solution. Other methods of solution also receive appropriate credit for correct work.

2. The requirements that have been established for the paragraph length response in Physics 1 and Physics 2 can be found on AP Central at https://secure-media.collegeboard.org/digitalServices/pdf/ap/paragraph-length-response.pdf.

3. Generally, double penalty for errors is avoided. For example, if an incorrect answer to part (a) is correctly substituted into an otherwise correct solution to part (b), full credit will usually be awarded. One exception to this may be cases when the numerical answer to a later part should be easily recognized as wrong, e.g., a speed faster than the speed of light in vacuum.

4. Implicit statements of concepts normally receive credit. For example, if use of the equation expressing a particular concept is worth one point, and a student's solution embeds the application of that equation to the problem in other work, the point is still awarded. However, when students are asked to derive an expression it is normally expected that they will begin by writing one or more fundamental equations, such as those given on the exam equation sheet. For a description of the use of such terms as "derive" and "calculate" on the exams, and what is expected for each, see "The Free-Response Sections—Student Presentation" in the *AP Physics; Physics C: Mechanics, Physics C: Electricity and Magnetism Course Description* or "Terms Defined" in the *AP Physics 1: Algebra-Based and AP Physics 2: Algebra-Based Course and Exam Description*.

5. The scoring guidelines typically show numerical results using the value $g = 9.8 \text{ m/s}^2$, but use of 10 m/s^2 is of course also acceptable. Solutions usually show numerical answers using both values when they are significantly different.

6. Strict rules regarding significant digits are usually not applied to numerical answers. However, in some cases answers containing too many digits may be penalized. In general, two to four significant digits are acceptable. Numerical answers that differ from the published answer due to differences in rounding throughout the question typically receive full credit. Exceptions to these guidelines usually occur when rounding makes a difference in obtaining a reasonable answer. For example, suppose a solution requires subtracting two numbers that should have five significant figures and that differ starting with the fourth digit (e.g., 20.295 and 20.278). Rounding to three digits will lose the accuracy required to determine the difference in the numbers, and some credit may be lost.

2017 SCORING GUIDELINES

Question

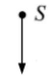
15 points total | **Distribution of ints**

(a)

i. 1 point

For correctly drawing a single vector pointing upward at point *R* — 1 point

ii. 1 point



For correctly drawing a single vector pointing downward at point *S* — 1 point

(b)

i. 2 points

For using Gauss's law to calculate the electric flux — 1 point

$$\Phi = \frac{Q}{\varepsilon_0} = \frac{\rho V}{\varepsilon_0}$$

For a correct answer — 1 point

$$\Phi = \frac{\rho_0 A h}{\varepsilon_0}$$

ii. 3 points

For correctly applying Gauss's law to the slab — 1 point

$$\frac{Q}{\varepsilon_0} = \oint \vec{E} \cdot d\vec{A} = EA_{top} + EA_{bottom}$$

For substituting the flux from part (b)(i) into equation above and for including the contributions of the top and bottom parts of the Gaussian surface — 1 point

$$\frac{\rho_0 A h}{\varepsilon_0} = 2EA$$

For correctly relating *h* to 2*z* — 1 point

$$\frac{\rho_0 A(2z)}{\varepsilon_0} = 2EA$$

$$E = \frac{\rho_0 z}{\varepsilon_0}$$

2017 SCORING GUIDELINES

Question 1 (continued)

Distribution of points

(c)

i. 1 point

Selecting "$z_0 < 0$"

For a correct justification — 1 point

Example: The electric field due to the plates alone is directed toward the top of the page. Therefore, the net electric field can only be zero where the electric field of the slab is directed toward the bottom of the page. So the net electric field can only be zero when $z_0 < 0$.

ii. 3 points

For setting the net electric field between the plates equal to zero and relating it to the sum of the electric fields of the plates and the slab — 1 point

$$E_{total} = 0 = E_{plate} + E_{slab}$$

For using the correct formula for the electric field between the plates regardless of sign — 1 point

$$\frac{\sigma}{\varepsilon_0} = -\frac{\rho_0 z_0}{\varepsilon_0}$$

$$z_0 = -\frac{\sigma}{\rho_0}$$

Substitute into equation above

$$z_0 = -\frac{\left(2.0 \times 10^{-6}\ \mathrm{C/m^2}\right)}{\left(1.0 \times 10^{-3}\ \mathrm{C/m^3}\right)}$$

For an answer that is consistent with the formula provided by the student above (must include units) — 1 point

$$z_0 = -2.0 \times 10^{-3}\ \mathrm{m}$$

2017 SCORING GUIDELINES

Question 1 (continued)

Distribution of points

(d) 4 points

For using the sum of the electric potential of the slab and the plates as the total potential difference between the center and top of the slab — 1 point

$\Delta V = \Delta V_{slab} + \Delta V_{plate}$

$\Delta V = \int E_{total}\, dr = \int \left(E_{slab} + E_{plate}\right) dr$

$\Delta V = \int E_{slab} dr + \int E_{plate}\, dr$

For integrating with proper limits or constants of integration — 1 point

$$\Delta V = \int_{z=0}^{z=0.005} \frac{\rho_0 z}{\varepsilon_0} dz + \int_{z=0}^{z=0.005} \frac{\sigma}{\varepsilon_0} dz$$

For correctly integrating each term regardless of whether they contain the correct expressions — 1 point

$$\Delta V = \frac{\rho_0}{\varepsilon_0}\left[\frac{z^2}{2}\right]_{z=0}^{z=0.005} + \frac{\sigma}{\varepsilon_0}[z]_{z=0}^{z=0.005} = \frac{\rho_0}{2\varepsilon_0}\left(0.005^2 - 0\right) + \frac{\sigma}{\varepsilon_0}(0.005 - 0)$$

$$\Delta V = \frac{\rho_0 z^2}{2\varepsilon_0} + \frac{\sigma z}{\varepsilon_0}$$

$$\Delta V = \frac{\left(1.0 \times 10^{-3}\ \text{C/m}^3\right)\left(5.0 \times 10^{-3}\ \text{m}\right)^2}{(2)\left(8.85 \times 10^{-12}\ \text{C}^2/\text{N}\bullet\text{m}^2\right)} + \frac{\left(2.0 \times 10^{-6}\ \text{C/m}^2\right)\left(5.0 \times 10^{-3}\ \text{m}\right)}{\left(8.85 \times 10^{-12}\ \text{C}^2/\text{N}\bullet\text{m}^2\right)}$$

For a correct answer — 1 point

$\Delta V = 2540\ \text{V}$

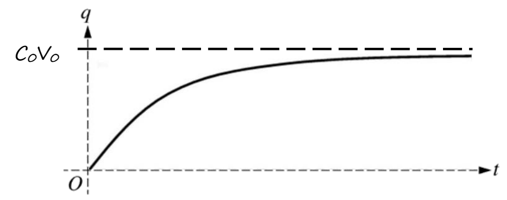
2017 SCORING GUIDELINES

Question

15 points total

Distribution of points

(a) 3 points

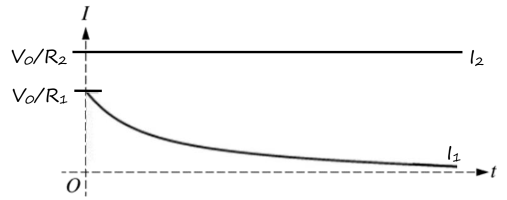


For a concave down curve starting at the origin — 1 point

For a horizontal asymptote — 1 point

For properly labeling the horizontal asymptote — 1 point

(b) 4 points



For showing that I_2 is horizontal with the correct vertical intercept — 1 point

For showing that I_1 is concave up and asymptotic to I = 0 — 1 point

For correctly labeling the vertical intercept of the I_1 graph — 1 point

For drawing the I_2 graph always above the I_1 graph — 1 point

(c) 2 points

Select "$\Delta t_C < \Delta t_D$"

For indicating that the equivalent resistance during discharging is greater than during charging — 1 point

For a statement relating the greater resistance to the greater time constant, or to a smaller current — 1 point

Example: Because the resistance as the capacitor discharges is greater than when it charges, the time constant is larger for discharging. Therefore, the time to charge to 50% of its maximum charge is less than the time to discharge to 50% of its maximum charge.

2017 SCORING GUIDELINES

Question 2 (continued)

Distribution of points

(d)

i. 2 points

For using a correct statement of Ohm's law or loop rule with the switch open — 1 point

$V = IR$

$I = \dfrac{V_C}{R_{tot}} = \dfrac{V_0}{R_1 + R_2}$

Substitute correct values into equation above

$I = \dfrac{(1.5\text{ V})}{(100\ \Omega + 150\ \Omega)}$

For a correct answer — 1 point

$I = 6.0\text{ mA}$ with units, or 0.006 without units

ii. 1 point

For a correct justification — 1 point

Example: Once the capacitor begins to discharge, the charge stored in the capacitor will decrease and the potential difference across the capacitor decreases. Therefore, the current through resistor R_2 decreases.

(e)

i. 1 point

For correctly substituting into an equation for the energy stored in a capacitor, including units for numerical values — 1 point

$U = \dfrac{1}{2}CV^2 = \dfrac{1}{2}(80\ \mu\text{F})(1.5\text{ V})^2 = 90\ \mu\text{J}$

ii. 2 points

For setting up a valid equation or argument to calculate the energy dissipated by resistor R_1 — 1 point

$E_{dis} = Pt = I^2Rt \therefore E_{dis} \sim R \therefore E_{dis,1} = E_{dis,tot}\dfrac{R_1}{(R_1 + R_2)}$

For correctly substituting into the equation above — 1 point

$E_{dis,1} = (90\ \mu\text{J})\dfrac{(150\ \Omega)}{(150\ \Omega + 100\ \Omega)} = 54\ \mu\text{J}$

Alternate Solution on next page.

AP Physics C: **Electricity and Magnetism: 2017**

2017 SCORING GUIDELINES

Question 2 (continued)

Distribution of points

(e)(ii) continued

Alternate Solution — *Alternate Points*

Derive an equation for the current through resistor R_1 as a function of time

$I(t) = I_{\text{MAX}}e^{-t/\tau} = \dfrac{V_{\text{MAX}}}{(R_1 + R_2)}e^{-t/(R_1+R_2)C} = \dfrac{(1.5\text{ V})}{(250\ \Omega)}e^{-t/(250\ \Omega)(80\ \mu\text{F})}$

$I(t) = (6.0\text{ mA})e^{-t/(0.02)}$

For using a correct formula with integral calculus to calculate the energy dissipated by resistor R_1 — 1 point

$E = \int Pdt = \int I^2Rdt = \int I(t)^2 R_1 dt = \int\left((6.0\text{ mA})e^{-t/(0.02)}\right)^2(150\ \Omega)dt$

For integrating the above equation with correct limits or constants of integration — 1 point

$E = (0.0054)\displaystyle\int_{t=0}^{t=\infty}\left(e^{-t/(0.02)}\right)^2 dt = (0.0054)\int_{t=0}^{t=\infty} e^{-100t}dt = (0.0054)\left[\frac{e^{-100t}}{(-100)}\right]_{t=0}^{t=\infty}$

$E = \left(-5.4\times10^{-5}\right)\left(e^{-\infty} - e^{0}\right) = 54\ \mu\text{J}$

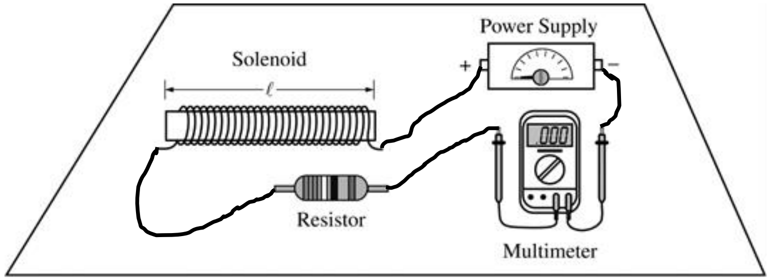
2017 SCORING GUIDELINES

Question

15 points total | **Distribution of points**

(a)

i. 2 points



For connections that create a circuit with the power supply, solenoid, and resistor in series with each other — 1 point

For connections that create a circuit with the multimeter in series with the inductor/resistor combination — 1 point

ii. 1 point

For selecting the answer consistent with the answer in part (a)(i) — 1 point

iii. 3 points

For selecting point *B* — 1 point

For any indication that the magnetic field outside the solenoid is less than inside the solenoid — 1 point

For any indication that the closer you are to the center of the solenoid, the better the approximation of an ideal solenoid due to the lack of edge effects — 1 point

Example: The equation for the magnetic field for a solenoid is for an ideal solenoid. This does not work outside the solenoid (this eliminates *C* and *D*). In addition, as you approach the edge of the solenoid, the ideal approximation is not as accurate (this eliminates *A*). Thus, point *B* gives the best approximation of an ideal solenoid.

2017 SCORING GUIDELINES

Question 3 (continued)

Distribution of points

(b) 2 points

For any indication that Solenoid 1 has more turns per unit length — 1 point

For any indication that Solenoid 1 is longer and therefore more like an ideal solenoid — 1 point

Examples:

The equation for the magnetic field of a solenoid $(B = \mu_0 nI)$ is based on an ideal solenoid in which you can ignore edge effects. Because Solenoid 1 has more turns per unit length, it is a better approximation of an ideal solenoid and thus its slope will give a better value for the permeability of free space.

The slope for Solenoid 1 is closer to the accepted value than the slope for Solenoid 2; therefore, the graph for Solenoid 1 is better.

(c)

i. 3 points

For correctly calculating the slope for the solenoid chosen in part (b) using the best-fit line and not the data points — 1 point

$$\text{slope} = \frac{(y_2 - y_1)}{(x_2 - x_1)} = \frac{(10-4)\left(\text{T}\times 10^{-5}\right)}{(75-24)(\text{A/m})} = 1.17\times 10^{-6}\ \text{T}\bullet\text{m/A}$$

For correctly relating the magnetic permittivity of free space to the slope — 1 point

$\mu_0 =$ slope

For correct units — 1 point

$\mu_0 = 1.17\times 10^{-6}\ \text{T}\bullet\text{m/A}$

For Solenoid 2

$$\text{slope} = \frac{(y_2 - y_1)}{(x_2 - x_1)} = \frac{(8-4)\left(\text{T}\times 10^{-5}\right)}{(82-35)(\text{A/m})} = 8.51\times 10^{-7}\ \text{T}\bullet\text{m/A}$$

ii. 1 point

For using a correct equation for % error including the substitution of the accepted and the measured values — 1 point

$$\%\ \text{error} = \frac{|\text{acc} - \text{exp}|}{\text{acc}}\times 100\% = \frac{\left|\left(1.26\times 10^{-6}\right) - \left(1.18\times 10^{-6}\right)\right|}{\left(1.26\times 10^{-6}\right)}\times 100\% = 6.35\%$$

For Solenoid 2

$$\%\ \text{error} = \frac{|\text{acc} - \text{exp}|}{\text{acc}}\times 100\% = \frac{\left|\left(1.26\times 10^{-6}\right) - \left(8.51\times 10^{-7}\right)\right|}{\left(1.26\times 10^{-6}\right)}\times 100\% = 32.4\%$$

2017 SCORING GUIDELINES

Question 3 (continued)

	Distribution of points
(d)	
i. 1 point	
For a correct explanation involving any extraneous *B* fields	1 point
Example: A component of Earth's magnetic field is in the direction of the inductor's magnetic field.	
ii. 2 points	
For stating that either the solenoid or the circuit has near zero resistance	1 point
For stating that as a result of near zero resistance the current becomes very high	1 point
Example: The inductor has near zero resistance. Therefore, without the resistor in series with it, the inductor will draw a near infinite current that the multimeter cannot handle.	

AP® Physics C: Electricity and Magnetism 2016 Scoring Guidelines

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Question

15 points total — **Distribution of points**

3 points

For indicating that the total potential is the sum of the potential from individual point charges — 1 point

ample using point B: $V_B = 0 = V_1 + V_2$

orrectly substituting into the above equation (signs are ignored at this step) — 1 point

$-V_1 = V_2$

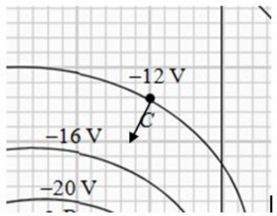
$-\dfrac{kq_1}{r_1} = \dfrac{kq_2}{r_2}$

$-\dfrac{q_1}{(5 \times 0.5m)} = \dfrac{(2.0 \text{ nC})}{(2 \times 0.5 \text{ m})}$

For a correct answer with correct sign and units — 1 point

$q_1 = -5.0 \text{ nC}$

2 points



For drawing a vector perpendicular to the equipotential line for C — 1 point

For drawing a vector in the direction of the -16 V line — 1 point

2 points

For using the equation relating the electric field to potential difference — 1 point

$E = -\dfrac{dV}{dx}$

$|E| \simeq \dfrac{\Delta V}{\Delta x}$

For substituting values from the figure — 1 point

$E = \dfrac{(-20 \text{ V} - (-24 \text{ V}))}{(2 \times 0.1 \text{ m})}$

$E = 20 \text{ N/C}$

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Question 1 (continued)

Distribution of points

2 points

For using a correct equation for the electric flux — 1 point

$\Phi_E = \dfrac{q_{enc}}{\varepsilon_0}$

$\Phi_E = \dfrac{(2.0 \text{ nC})}{\left(8.85 \times 10^{-12} \text{ C}^2 / \left(\text{N} \bullet \text{m}^2\right)\right)}$

For a correct answer with units — 1 point

$\Phi_E = 226 \left(\text{N} \bullet \text{m}^2\right) / \text{C}$

(

2 points

sing an equation that relates the work done to the change in potential energy — 1 point

$W = -q\Delta V = -(1.6 \times 10^{-19} \text{ C})(-4 \text{ V} - (4 \text{ V}))$

For a correct answer including sign and units — 1 point

$W = 1.28 \times 10^{-18} \text{ J} = 8.0 \text{ eV}$

2 points

ndicating that the kinetic energy of the proton at E will be equal to the work done — 1 point

$W = \Delta K = \dfrac{1}{2}mv^2$

orrectly substituting the answer from part (e) i. into the above equation — 1 point

$\left(1.28 \times 10^{-18} \text{ J}\right) = \left(\dfrac{1}{2}\right)\left(1.67 \times 10^{-27} \text{ kg}\right)v^2$

$v = 3.92 \times 10^4 \text{ m/s}$

) 2 points

;orrectly selecting Left — 1 point

For a correct justification — 1 point

Example: Electrons accelerate in the direction perpendicular to equipotential surfaces and toward higher potential. Therefore, at point B, an electron would accelerate toward the left.

No points are earned if the wrong answer is selected.

SCORING GUIDELINES

Question

15 points total **Distribution of points**

2 points

For selecting “It is the same through both.” 1 point

For a correct justification 1 point

Example: The sample of wire and the resistor are in series with each other and therefore will have the same current.

Note: Because the voltmeter is ideal, it will have no effect on the result.

No points are earned if the wrong answer is selected.

2 points

For selecting “It will depend on the resistance of the sample.” 1 point

For a correct justification including argument using Ohm’s law, voltage drop across resistors, etc. 1 point

Example: Because the sample of wire has resistance, it cannot be known whether the wire of the resistor has the greatest resistance and which has the higher potential difference across it. Therefore, it will depend on the resistance of the wire sample.

No points are earned if the wrong answer is selected.

(1 point

ndicating the correct quantities for each axis 1 point

Horizontal axis: I_R

Vertical axis: $V_r = \mathcal{E} - V_R$

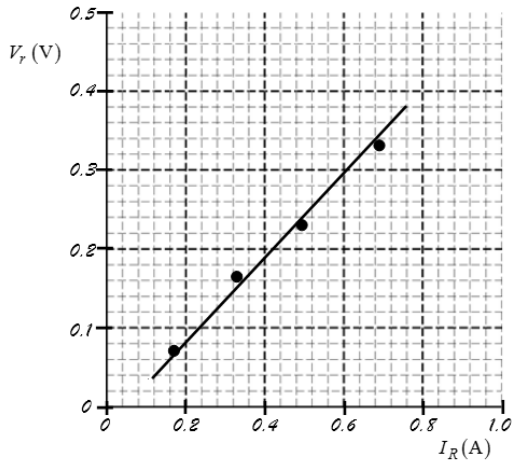
Note: Credit is received if the axes are reversed.

SCORING GUIDELINES

Question 2 (continued)

Distribution of points

3 points



For a correct scale that uses more than half the grid and for correctly labeling the axes including units 1 point

For correctly plotting given data 1 point

For drawing a straight line consistent with the given data 1 point

(2 points

For correctly calculating slope using the best-fit straight line and not data points 1 point

$$\text{slope} = \frac{(V_2 - V_1)}{(I_2 - I_1)} = \frac{(0.30 - 0.10)\ \text{V}}{(0.60 - 0.22)\ \text{A}} = 0.526\ \text{V/A}$$

Note: Linear regression gives $\text{slope} = 0.485\ \text{V/A}$. (Student must indicate that the value comes from a linear regression from the calculator, and the equation of the line must be present.)

For correctly relating r to the slope 1 point

$V_r = I_R r$, therefore the slope equals r

$r = 0.526\ \Omega$

Note: Linear regression gives $r = 0.485\ \Omega$.

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Question 2 (continued)

Distribution of points

) 1 point

For using the equation relating resistance to resistivity with the correct or consistent substitutions — 1 point

$R = \dfrac{\rho L}{A}$ so $\rho = \dfrac{AR}{L}$

$\rho = \dfrac{(\pi)\left(1.00 \times 10^{-3}\ \text{m}\right)^2 (0.526\ \Omega)}{(3.00\ \text{m})}$

$\rho = 5.51 \times 10^{-7}\ \Omega\text{•m}$

Note: Linear regression gives $\rho = 5.08 \times 10^{-7}\ \Omega\text{•m}$.

2 points

electing "Less than" with an attempt at a justification — 1 point
For a correct justification — 1 point
Example: The resistance calculated from the graph is the sum of the sample resistance plus the ammeter resistance because it is not ideal. The actual resistance is the calculated resistance minus the ammeter resistance, and therefore less than the calculated resistance.
oints are earned if the wrong answer is selected.

2 points

For selecting "Greater than" with an attempt at a justification — 1 point
For a correct justification — 1 point
Example: If the voltmeter is not ideal, that would add an additional resistor in parallel. A parallel resistor reduces the total resistance of the circuit. This would lead to an increase in current and a higher reading on the ammeter.
No points are earned if the wrong answer is selected.

;CORING GUIDELINES

Question

15 points total

Distribution of points

1 point

For selecting "Left" — 1 point

2 points

For selecting "Less than" — 1 point
For a correct justification — 1 point
Example: Because as the bar falls the flux at point C is increasing, the emf generated must create a magnetic field to oppose this change. Therefore, it will create a magnetic field to decrease the flux and thus decrease the magnetic field.
No points are earned if the wrong answer is selected.

2 points

For selecting "Greater than" — 1 point
For a correct justification — 1 point
Example: The field at point C, which is above the bar, is less than the original magnetic field, and point D is on the other side of the bar. Therefore, the direction of the magnetic field from the bar at point D is the opposite of the direction at point C, so the net magnetic field at D when the bar is falling must be greater than the original magnetic field.
No points are earned if the wrong answer is selected.

(4 points

For correctly applying Newton's second law to the motion of the bar — 1 point

$F_{net} = Mg - F_M = Mg - BIL$

$I = \mathcal{E}/R$

For attempting to use Faraday's law to obtain an expression for the emf in the bar — 1 point

$\mathcal{E} = d\Phi/dt = BL(dx/dt)$

For correctly using the expression for emf to obtain an expression for the current — 1 point

$I = \dfrac{BL(dx/dt)}{R} = \dfrac{BLv}{R}$

$Ma = Mg - B\dfrac{BLv}{R}L$

$a = g - \dfrac{B^2L^2v}{MR}$

vriting the acceleration as dv/dt — 1 point

$\dfrac{dv}{dt} = g - \dfrac{B^2L^2v}{MR}$

SCORING GUIDELINES

Question 3 (continued)

Distribution of points

2 points

For setting the net force at terminal velocity equal to zero — 1 point

$$0 = Mg - \frac{B^2L^2v_T}{R}$$

$$\frac{B^2L^2v_T}{R} = Mg$$

n answer consistent with part (c) — 1 point

$$v_T = \frac{MgR}{B^2L^2}$$

(1 point

For a correct or consistent substitution in an appropriate power equation — 1 point

$$P = I^2R \quad \text{or} \quad V = IR$$

$$\frac{BLv_T}{R} = I$$

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

Alternate Solution — *Alternate points*

For a correct or consistent substitution in an appropriate power equation — *1 point*

$$P = I^2R$$

$$Mg = BIL$$

$$I = \frac{Mg}{BL}$$

$$P = \frac{M^2g^2R}{B^2L^2}$$

SCORING GUIDELINES

Question 3 (continued)

Distribution of points

) 3 points

Using the equation from part (c)

$$\frac{dv}{dt} = g - \frac{B^2L^2v}{MR}$$

$$\frac{dv}{dt} = \frac{-B^2L^2}{MR}\left(v - \frac{MRg}{B^2L^2}\right)$$

For attempting separation of variables — 1 point

$$\frac{dv}{v - \frac{MRg}{B^2L^2}} = \frac{-B^2L^2}{MR}dt$$

For attempting to integrate with the correct limits or the correct constant of integration — 1 point

$$\int_{v'=0}^{v'=v(t)} \frac{1}{\left(v' - \frac{MRg}{B^2L^2}\right)} dv' = \int_{t'=0}^{t'=t} \frac{-B^2L^2}{MR}dt'$$

$$\ln\left[v' - \frac{MRg}{B^2L^2}\right]_{v'=0}^{v'=v(t)} = \frac{-B^2L^2}{MR}t$$

$$\ln\left(\frac{v(t) - \frac{MRg}{B^2L^2}}{\frac{MRg}{B^2L^2}}\right) = \frac{-B^2L^2}{MR}t$$

For a correct answer — 1 point

$$v(t) = \frac{MRg}{B^2L^2}\left(1 - e^{-\frac{B^2L^2}{MR}t}\right)$$

ng a trial solution in the differential equation and verifying its correctness is also acceptable.