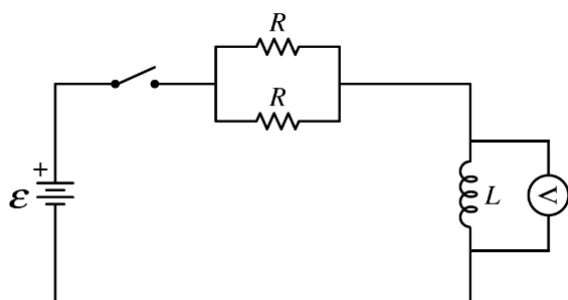


Question 2: Free-Response Question**15 points**

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

Example Response

- (a)(ii) For a procedure that indicates that the voltmeter should be used to measure the potential difference for at least one time **1 point**

For measuring the potential difference from immediately after the switch is closed to when steady-state conditions have been established or during a time interval that would allow the time constant to be determined **1 point**

Example Response

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

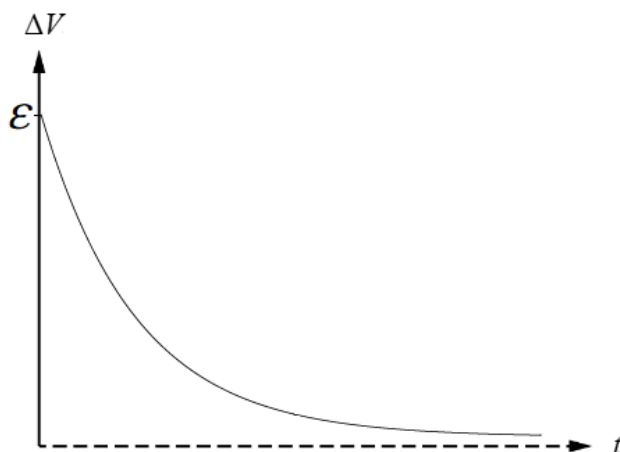
Total for part (a) 3 points

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

For a concave-up and decreasing curve **1 point**

For a curve that asymptotically approaches zero, or a curve that starts at the origin and approaches a horizontal asymptote that is consistent with the placement of the voltmeter in the response in part (a)(i) **1 point**

For including a vertical intercept or a horizontal asymptote that is consistent with the placement of the voltmeter in the response in part (a)(i) that is correctly labeled as $\mathcal{E}$ **1 point**

Example Response

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

Alternate Solution

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

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

Alternate Solution

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

Example Response

The data in the graph should be fit with an exponential function for the equation

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

Alternate Example Response

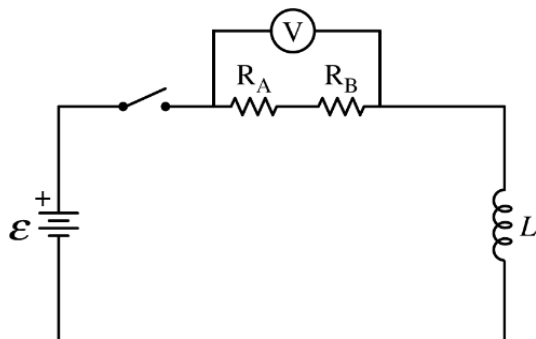
The potential difference at 0.37ε along the vertical axis corresponds to the time constant along the horizontal axis. Because the time constant is equal to $\frac{2L}{R}$, and L is known, R can be calculated.

Total for part (b) 6 points

(c)	For a multi-step derivation that begins with an attempt at using Kirchhoff's loop rule	1 point
Example Response		
$\mathcal{E} - \Delta V_R - \Delta V_L = 0$		
For indicating that the potential difference across the parallel combination of resistors is $I\left(\frac{R}{2}\right)$		1 point
For indicating that the absolute value of the potential difference across the inductor is $L \frac{dI}{dt}$		1 point
Example Solution		
$\mathcal{E} - \Delta V_R - \Delta V_L = 0$		
$\mathcal{E} - I\left(\frac{R}{2}\right) - L \frac{dI}{dt} = 0$		
$\frac{\mathcal{E}}{L} - \frac{IR}{2L} = \frac{dI}{dt}$		
$-\frac{R}{L}\left(\frac{I}{2} - \frac{\mathcal{E}}{R}\right) = \frac{dI}{dt}$		
Total for part (c)		3 points
(d)	For selecting $ \Delta V_2 > \Delta V_1 $ with an attempt at a relevant justification	1 point
For indicating that the potential difference across the original inductor is zero when steady-state conditions are established		1 point
For indicating that the potential difference across the inductor of nonnegligible resistance is nonzero when steady-state conditions are established		1 point
Example Response		
$ \Delta V_2 > \Delta V_1 $. The potential difference ΔV_1 across the original, ideal inductor is zero at steady state. The potential difference across the new inductor would be nonzero due to the inductor's nonnegligible resistance. The value of $ \Delta V_2 $ would be the product of the steady-state current and the inductor's resistance.		
Total for part (d)		3 points
Total for question 2		15 points

Question 2: 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**

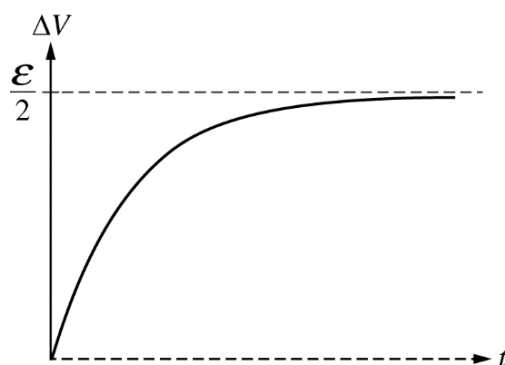
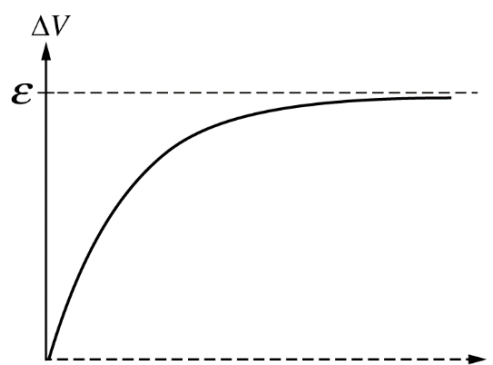
For measuring the potential difference from immediately after the switch is closed to when steady-state conditions have been established or until a time at which the time constant can be determined **1 point**

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

$$V_R = \mathcal{E} \left(1 - e^{-t \frac{2R}{L}} \right). \text{ Because } \mathcal{E} \text{ and } L \text{ are known, } R \text{ can be calculated.}$$

Alternate Example Response

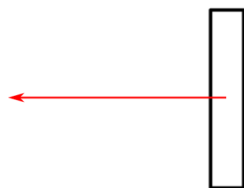
The potential difference at $0.63\mathcal{E}$ along the vertical axis corresponds to the time constant along the horizontal axis. Because the time constant is equal to $\frac{L}{2R}$, and L is known, R can be calculated.

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 $L \frac{dI}{dt}$ 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 $\Delta V_2 < \Delta V_1$ 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 $\Delta V_2 < \Delta V_1$, 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 $\Delta V_2 < \Delta V_1$, 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 2: Free-Response Question**15 points**

- (a) For drawing an arrow pointing to the left with no extraneous arrows

1 point**Example Response****Total for part (a) 1 point**

(b)(i) For using Faraday's law to calculate the value of the induced emf **1 point**

Scoring Note: This point may be earned without the negative sign or a numerical answer.

Example Response

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

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

For a correct substitution of v for $\frac{dx}{dt}$ **1 point**

Scoring Note: A student can earn points 1 and 2 of part (b)(i) by starting with the expression

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

Example Response

$$\mathcal{E} = -BL\left(\frac{dx}{dt}\right)$$

$$BL\frac{dx}{dt} = BLv$$

For substituting the correct resistance into an equation for Ohm's law to solve for the current **1 point**

Example Solution

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

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

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

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

$$\mathcal{E} = -(0.50 \text{ T})(0.40 \text{ m})(2.5 \text{ m/s})$$

$$\mathcal{E} = -0.50 \text{ V}$$

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

$$I = \frac{|\mathcal{E}|}{R}$$

$$I = \frac{|-0.50 \text{ V}|}{0.30 \Omega} = 1.7 \text{ A}$$

(b)(ii)	For substituting the current or an expression for the current obtained from part (b)(i) into an appropriate equation that is related to the magnetic force exerted on the bar	1 point
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Example Responses

$$\vec{F} = \int I d\vec{\ell} \times \vec{B}$$

$$F = ILB$$

$$F = (1.7 \text{ A})(0.4 \text{ m})(0.5 \text{ T})$$

$$F = 0.33 \text{ N}$$

OR

$$\vec{F} = \int I d\vec{\ell} \times \vec{B}$$

$$F = ILB$$

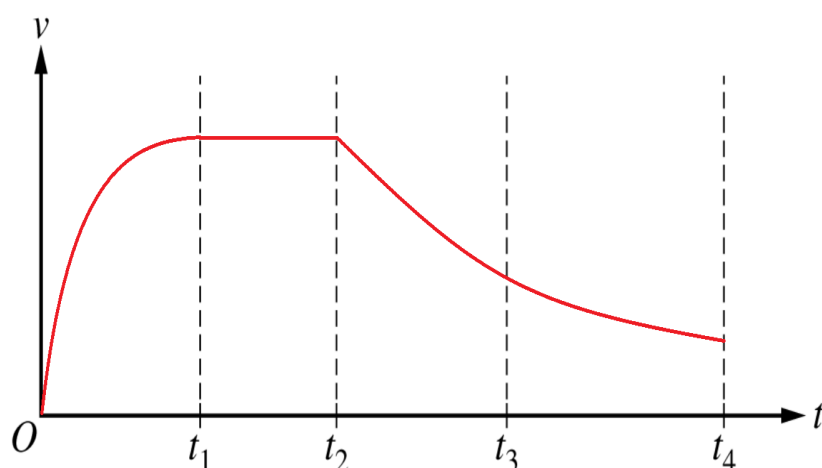
$$F = \left(\frac{BLv}{R} \right) LB$$

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

$$F = \frac{(0.5 \text{ T})^2 (0.4 \text{ m})^2 (2.5 \text{ m/s})}{0.3 \Omega}$$

$$F = 0.33 \text{ N}$$

Total for part (b)		4 points
(c)	For drawing a curve that starts at the origin, is increasing, and is concave down from $t = 0$ to t_1	1 point
	For drawing a horizontal line from t_1 to t_2	1 point
	For drawing a curve that is decreasing and concave up from t_2 to t_4	1 point
	For drawing a curve that is differentiable at t_3 with a nonzero slope	1 point

Example Response**Total Points for part (c) 4 points**

(d)(i)	For a correct answer with units ($0.15\ \Omega$)	1 point
---------------	--	----------------

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

Example Response

$$\frac{1}{R_p} = \sum_i \frac{1}{R_i}$$

$$\frac{1}{R_p} = \frac{1}{0.3\ \Omega} + \frac{1}{0.3\ \Omega}$$

$$\frac{1}{R_p} = \frac{2}{0.3\ \Omega}$$

$$R_p = 0.15\ \Omega$$

(d)(ii)	For a statement that correctly describes the inverse relationship between resistance and current (e.g., as resistance decreases current increases)	1 point
----------------	--	----------------

For a statement that describes the direct relation between current and force (e.g., as current increases force increases)	1 point
---	----------------

For a statement that describes the direct relation between force and acceleration (e.g., as force increases acceleration increases)	1 point
---	----------------

Scoring Note: Full credit can be earned with a justification that is consistent with the resistance calculated in part (d)(i).

Example Response

Since there is less resistance in the new circuit, there will be more current in the new circuit, so a larger force on the bar. Thus, since the force on the bar is larger, the new acceleration is greater than the original acceleration.

Total for part (d)	4 points
---------------------------	-----------------

-
- (e) For correctly indicating **one** of the following, with an attempt at a relevant justification: **1 point**
- Decreasing B
 - Decreasing L
 - Increasing m
-

For correctly justifying the identified modification that will result in a smaller induced potential difference across the original resistor **1 point**

Example Responses

The potential difference due to the induced emf across the original resistor is described by the equation $\mathcal{E} = -BLv$. Induced potential difference $\mathcal{E}$ is proportional to B . Therefore, if the magnitude of the magnetic field is smaller than $B = 0.5 \text{ T}$ in the new scenario compared to the original scenario, $\mathcal{E}$ would be smaller.

OR

The potential difference due to the induced emf across the original resistor is described by the equation $\mathcal{E} = -BLv$. The induced potential difference $\mathcal{E}$ is proportional to L , which represents the distance the conducting rails are separated. Therefore, if L is smaller than $L = 0.4 \text{ m}$, $\mathcal{E}$ would be smaller.

OR

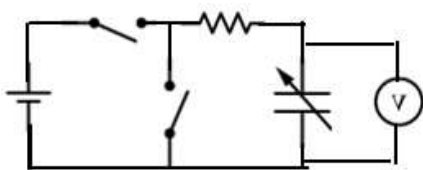
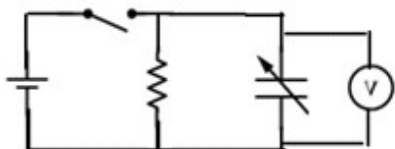
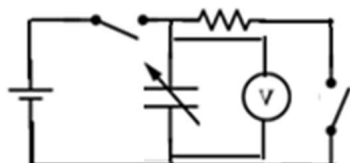
The potential difference due to the induced emf across the original resistor is described by the equation $\mathcal{E} = -BLv$. If the mass of the bar is greater, the velocity entering the magnetic field is less. The induced potential difference $\mathcal{E}$ is proportional to v . Therefore, a smaller v due to a greater mass will induce a smaller $\mathcal{E}$.

Total for part (e) 2 points

Total for question 2 15 points

Question 2: Free-Response Question**15 points**

- | | | |
|------------|--|----------------|
| (a) | For a schematic diagram with the capacitor in series with the resistor | 1 point |
| | OR | |
| | For a schematic diagram with the resistor on the parallel path | |
| | For a schematic diagram with the voltmeter in parallel with the capacitor | 1 point |
| | For a schematic diagram that uses a switch to connect the battery to the capacitor | 1 point |
| | For a schematic diagram that uses a switch that allows the capacitor to discharge through the resistor | 1 point |

Example Responses**OR****OR****Total for part (a) 4 points**

- | | | |
|------------|--|----------------|
| (b) | For using an appropriate loop equation | 1 point |
|------------|--|----------------|

Example Response

$$V_C - V_R = 0$$

- | | |
|--|----------------|
| For correctly substituting $\frac{q}{C}$ and IR in a loop equation consistent with the first point | 1 point |
|--|----------------|

Example Response

$$\frac{q}{C} = IR$$

For using a differential expression consistent with the loop rule in the first point that includes a substitution of $I = -\frac{dq}{dt}$ for the current

1 point**Example Response**

$$\frac{q}{C} = -\frac{dq}{dt} R$$

$$-\frac{1}{RC} dt = \frac{1}{q} dq$$

$$-\frac{1}{RC} \int_{t=0}^{t=t} dt = \int_{q=q_0}^{q=q} \frac{1}{q} dq$$

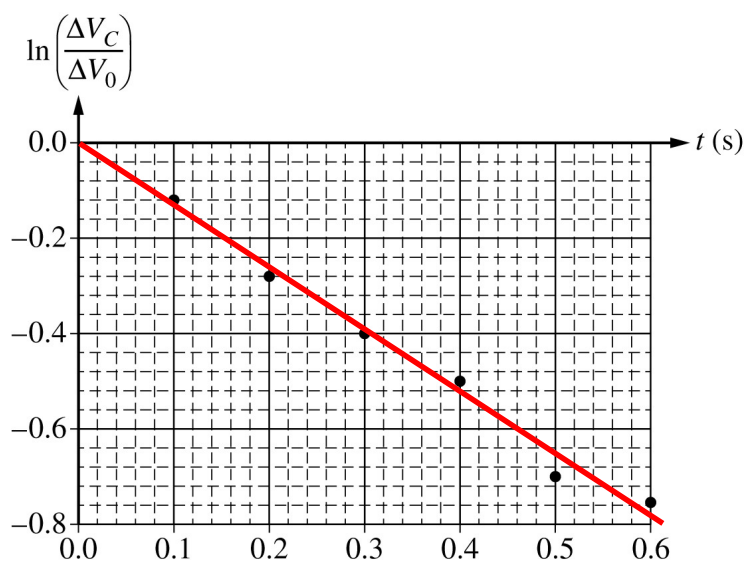
$$\frac{-t}{RC} = \ln\left(\frac{q(t)}{q_0}\right) \therefore \frac{q(t)}{q_0} = e^{-t/RC} \therefore \frac{q(t)}{C} = \frac{q_0}{C} e^{-t/RC} \therefore V(t) = V_0 e^{-t/RC}$$

Scoring Note: The point can be earned regardless of the sign used in the substitution of

$\frac{dq}{dt}$ for the current.

Total for part (b) 3 points

(c)(i) For drawing an appropriate best-fit line

1 point**Example Response**

-
- (c)(ii)** For using an appropriate equation to relate the unknown capacitance to the data **1 point**

Example Response

$$V(t) = V_0 e^{-t/RC} \therefore \frac{V(t)}{V_0} = e^{-t/RC} \therefore \ln\left(\frac{V(t)}{V_0}\right) = -\frac{t}{RC}$$

-
- For correctly calculating the slope using two points from the best-fit line **1 point**

Example Response

$$\text{slope} = \frac{\Delta\left(\ln\left(\frac{V}{V_0}\right)\right)}{\Delta t} = \frac{(-0.70 - (-0.40))}{(0.54 \text{ s} - 0.30 \text{ s})} = -1.25 \text{ s}^{-1}$$

Scoring Note: A response may earn this point regardless of the associated unit.

-
- For correctly relating the slope to the unknown capacitance **1 point**

Example Response

$$\text{slope} = -\frac{1}{RC} \therefore C = \frac{-1}{\text{slope} \times (R)} = \frac{-1}{(-1.25 \text{ s}^{-1}) \times (150 \text{ k}\Omega)} = 5 \mu\text{F}$$

Total for part (c) 4 points

-
- (d)** For selecting “Less steep” and an attempt at a relevant justification **1 point**

-
- For correctly relating the correct change in capacitance to the slope of the graph **1 point**

Example Response

Increasing the area of the plates increases the capacitance of the capacitor; thus, the magnitude of the slope will decrease.

Scoring Note: Part (d) is scored consistently with part (c).

Total for part (d) 2 points

-
- (e)(i)** Correct answer: “No”

-
- For selecting “No” AND correctly describing the effects of the internal resistance of the battery on the slope of the graph at $t = 0$ **1 point**

Example Response

No. The capacitor still discharges only through resistor R , so the slope is the same.

-
- | | | |
|----------------|---|----------------|
| (e)(ii) | For selecting “No” AND correctly describing the effects of the internal resistance of the battery on the initial value of the graph | 1 point |
|----------------|---|----------------|
-

Example Response

No. The best-fit line does not change, because the internal resistance of the battery does not affect the final potential difference across the charging capacitor.

Scoring Note: This point is scored with consistency with the circuit drawn in part (b).

Total for part (e) 2 points

Total for question 2 15 points

Question 2: Free-Response Question**15 points**

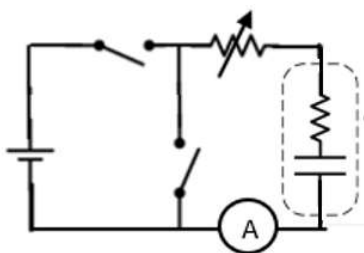
- (a) For a schematic diagram with the capacitor in series with the resistor **1 point**

Scoring Note: The response may earn this point even if the variable resistor is not included in the circuit diagram.

For a schematic diagram with the ammeter in series with the capacitor and resistor **1 point**

For a schematic diagram that uses a switch to connect the battery to the capacitor **1 point**

For a schematic diagram that uses a switch that allows the capacitor to discharge through the resistor **1 point**

Example Response

Total for part (a) 4 points

- (b) For using an appropriate loop equation by substituting a correct expression for the potential difference across the capacitor in terms of I , C , and r_C and IR for the potential difference across the variable resistor, if included **1 point**

Example Response

$$V_C - V_R = 0$$

$$\frac{q}{C} - Ir_C = IR \therefore \frac{q}{C} = I(R + r_C)$$

For substituting $R + r_C$ as the total resistance of the circuit **1 point**

Example Response

$$R_{\text{total}} = R + r_C$$

Scoring Notes:

- This point is earned if the above substitution is made anywhere in part (b).
- If the variable resistor is not included in the expression, accept expressions without R throughout.

For a correct differential equation consistent with the first point that could be used to determine the current I through the capacitor as a function of time t

1 point**Example Response**

$$\frac{dq}{dt} \frac{1}{C} = (R + r_C) \frac{dI}{dt}$$

$$-I \frac{1}{C} = (R + r_C) \frac{dI}{dt}; \quad I = -\frac{dq}{dt}$$

Where q is the charge on one plate of the capacitor that decreases over time

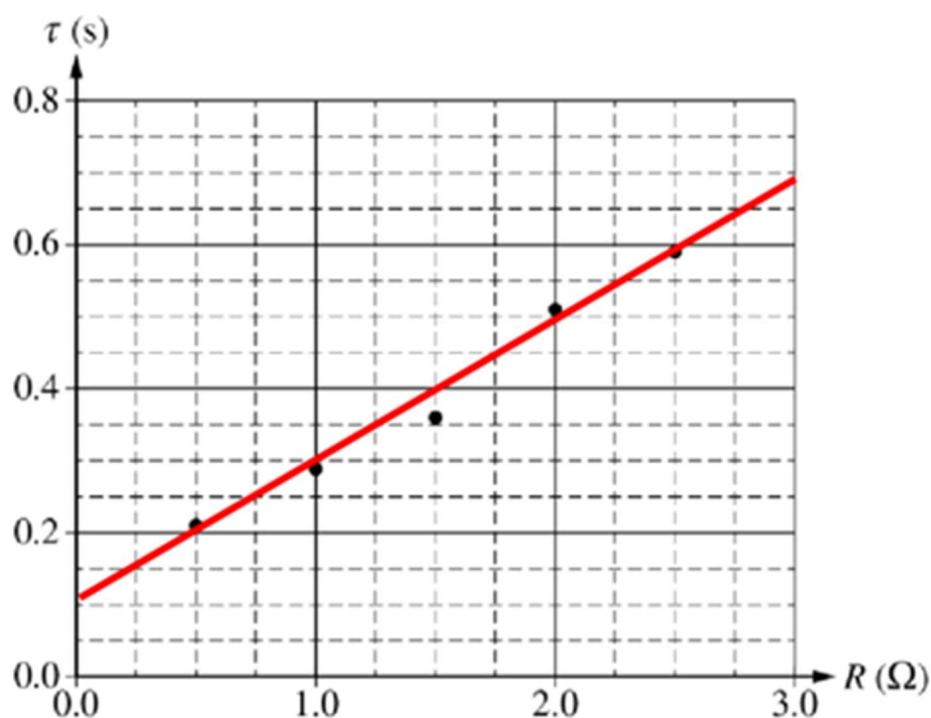
$$\frac{1}{I} \frac{dI}{dt} = \frac{-1}{C(R + r_C)}$$

$$\ln \frac{I}{I_0} = \frac{-t}{C(R + r_C)}$$

$$I = I_0 e^{\frac{-t}{C(R + r_C)}}$$

Total for part (b) 3 points

(c)(i) For drawing an appropriate best-fit line

1 point**Example Response**

(c)(ii) For correctly determining the slope of the line **1 point**

Example Response

$$\text{slope} = \frac{(0.24 - 0.08) \text{ s}}{(1.0 - 0.2) \Omega} = 0.2 \text{ F}$$

For using the equation $\tau = RC$ to determine that the slope must be C **1 point**

Example Response

$$\tau = RC$$

$$\tau = (R + r_C)C$$

$$\tau = CR + r_C C$$

For correctly relating the vertical intercept to the internal resistance of the capacitor **1 point**

Example Response

$$\text{Vertical intercept} = \tau_0 = r_C C$$

$$\text{Vertical intercept} = 0.08 \text{ s}$$

$$\begin{aligned} r_C &= \frac{\text{vertical intercept}}{C} \\ &= \frac{0.08 \text{ s}}{0.2 \text{ F}} \end{aligned}$$

$$r_C = 0.4 \Omega$$

Total for part (c) 4 points

(d) For selecting “Less than” and an attempt at a relevant justification **1 point**

For a correct justification that the internal resistance would be less due to the unknown resistance that is measured being the equivalent resistance of the ammeter and capacitor **1 point**

Example Response

The internal resistance of the ammeter would add to the internal resistance of the capacitor due to the fact the circuit elements are in series; this would result in an equivalent resistance that is measured in this experiment. Thus, the internal resistance of the capacitor is smaller than this equivalent resistance measured.

Total for part (d) 2 points

(e) For selecting “Remain unchanged” and an attempt at a relevant justification **1 point**

For a correct justification that the slope of the line is capacitance, which is independent of resistance **1 point**

Example Response

The relationship between the time constant and the resistance, the slope, is the capacitance, which does not change regardless of how large the value of the resistance is.

Scoring Note: This point is scored with consistency with the circuit drawn in part (a).

Total for part (e) 2 points

Total for question 2 15 points

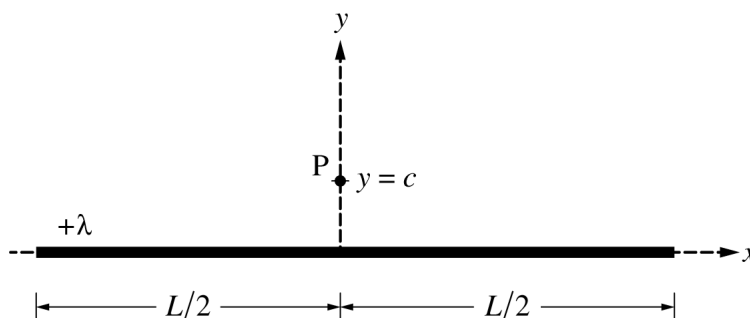
2019**AP[®]** **CollegeBoard**

AP[®] Physics C: Electricity and Magnetism

Scoring Guidelines Set 1

2019 SCORING GUIDELINES**General Notes About 2019 AP Physics Scoring Guidelines**

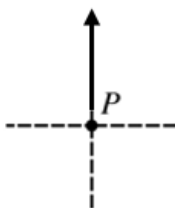
1. The solutions contain the most common method of solving the free-response questions and the allocation of points for this solution. Some also contain a common alternate solution. Other methods of solution also receive appropriate credit for correct work.
2. The requirements that have been established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

2019 SCORING GUIDELINES**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 $L \gg c$.

- (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 .	
<u>Note:</u> Credit is earned if the student draws the correct surface on the figure.	

2019 SCORING GUIDELINES**Question 1 (continued)**

(a) continued

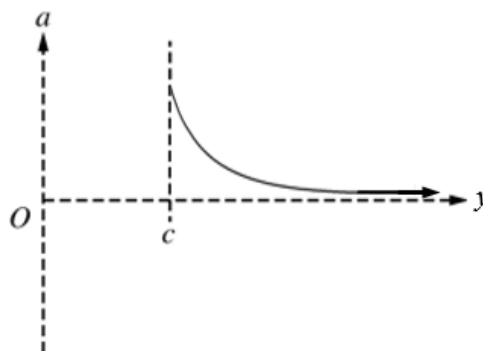
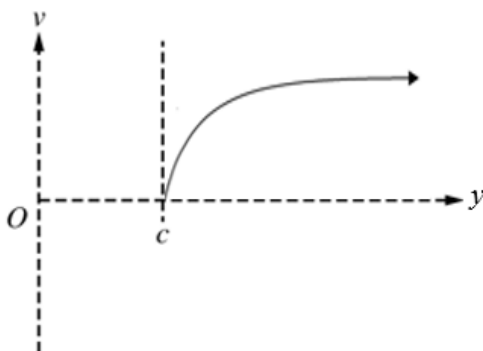
- iii. LO CNV-2.C, SP 5.A, 5.E
3 points

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
$\frac{q_{enc}}{\epsilon_0} = \int E \cdot dA \therefore \frac{Q}{\epsilon_0} = EA$		
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
$\frac{\lambda L}{\epsilon_0} = E(2\pi cL) \therefore E = \frac{\lambda}{2\pi\epsilon_0 c} = \frac{2k\lambda}{c}$		

- (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.

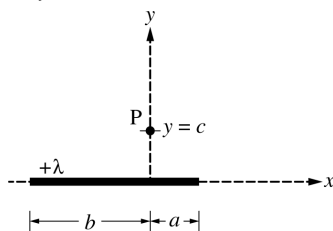


For a concave down graph for v as a function of position x that does not start at the origin		1 point
For a concave up graph for a as a function of position x that has an asymptote at the horizontal axis		1 point

2019 SCORING GUIDELINES

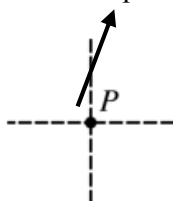
Question 1 (continued)

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

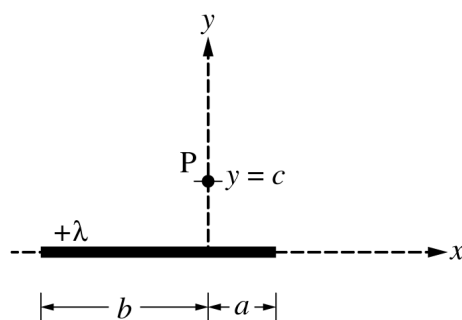
- (d) i. and ii. LO CNV-2.F, SP 7.A
1 point

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.	

2019 SCORING GUIDELINES**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.

$$E = \int \frac{1}{4\pi\epsilon_0} \frac{1}{r^2} dq$$

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.

$$\text{Horizontal component: } |E_x| = \frac{\lambda}{4\pi\epsilon_0} \int_{-b}^a \frac{x}{(c^2 + x^2)^{3/2}} dx$$

$$\text{Vertical component: } |E_y| = \frac{\lambda}{4\pi\epsilon_0} \int_{-b}^a \frac{y}{(c^2 + x^2)} dy$$

- (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
--	---------

2019 SCORING GUIDELINES**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.

2019 SCORING GUIDELINES

Question 2

15 points

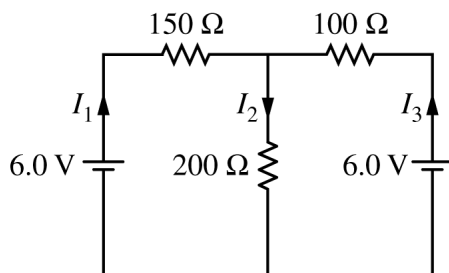


Figure 1

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)
- 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
$6 - 150I_1 - 200I_2 = 0$		
$6 - 100I_3 - 200I_2 = 0$		
$6 - 150I_1 + 100I_3 - 6 = 0$		
<u>Note:</u> Full credit is earned for two correct loop equations using loop currents.		

- 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
$I_1 - I_2 + I_3 = 0$ $-I_1 - 1.33I_2 = -.04 \therefore -4.33I_2 = -.10$ $-I_3 - 2I_2 = -.06$		
<u>Note:</u> 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
$-4.33I_2 = -.10 \therefore I_2 = 0.023\text{ A}$		

2019 SCORING GUIDELINES**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
$P = I^2 R = (0.023\ \text{A})^2 (200\ \Omega) \therefore P = 0.107\ \text{W}$		

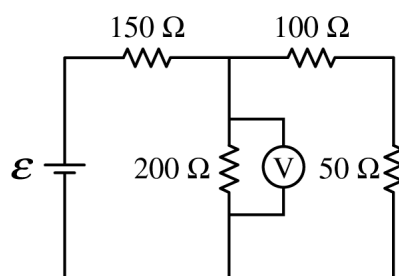


Figure 2

The two $6.0\ \text{V}$ 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 $4.4\ \text{V}$.

(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
$I = \frac{V}{R} = \frac{(4.4\ \text{V})}{(100\ \Omega + 50\ \Omega)} \therefore I = 0.029\ \text{A}$		

2019 SCORING GUIDELINES**Question 2 (continued)**

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

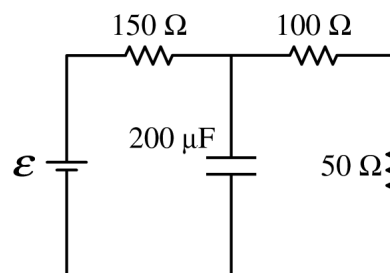
Calculate the voltage $\mathcal{E}$ of the battery.

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
$I_1 = I_2 + I_3 = \frac{(4.4\ \text{V})}{(200\ \Omega)} + 0.029\ \text{A} = 0.051\ \text{A}$	
For using a correct equation to determine the emf of the battery	1 point
$\mathcal{E} = I_1 R_1 + V_2 = (0.051\ \text{A})(150\ \Omega) + 4.4\ \text{V} = 12.1\ \text{V}$	
<i>Alternate Third Point</i>	
<i>For calculating the equivalent resistance of the circuit and substituting this resistance into a correct equation to determine the emf of the battery</i>	<i>1 point</i>
$R_T = 150\ \Omega + \frac{1}{\frac{1}{200\ \Omega} + \frac{1}{150\ \Omega}} = 236\ \Omega$	
$\mathcal{E} = I_1 R_T = (0.051\ \text{A})(236\ \Omega) = 12.0\ \text{V}$	
<i>Alternate Solution</i>	<i>Alternate Points</i>
<i>For using a correct equation to determine the equivalent resistance of the parallel resistors</i>	<i>1 point</i>
$\frac{1}{R_P} = \frac{1}{200\ \Omega} + \frac{1}{150\ \Omega} \therefore R_P = 86\ \Omega$	
<i>For correctly substituting the given potential difference and the calculated equivalent resistance to determine the total current of the circuit</i>	<i>1 point</i>
$I_T = \frac{(4.4\ \text{V})}{(86\ \Omega)} = 0.051\ \text{A}$	
<i>For calculating the equivalent resistance of the circuit and substituting into a correct equation to determine the emf of the battery</i>	<i>1 point</i>
$R_T = 150\ \Omega + 86\ \Omega = 236\ \Omega$	
$\mathcal{E} = I_1 R_T = (0.051\ \text{A})(236\ \Omega) = 12.0\ \text{V}$	

2019 SCORING GUIDELINES**Question 2 (continued)**

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

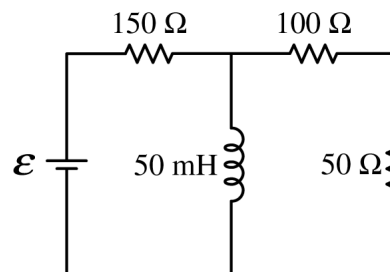
The $200\ \Omega$ resistor in the circuit in Figure 2 is replaced with a $200\ \mu\text{F}$ capacitor, as shown on the right, and the circuit is allowed to reach steady state. Calculate the current through the $50\ \Omega$ resistor.



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
$I = \frac{\mathcal{E}}{R_{\text{tot}}} = \frac{(12.1\ \text{V})}{(150\ \Omega + 100\ \Omega + 50\ \Omega)} = 40.3\ \text{mA}$	

- 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 $50\ \text{mH}$ 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.	

2019 SCORING GUIDELINES**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.

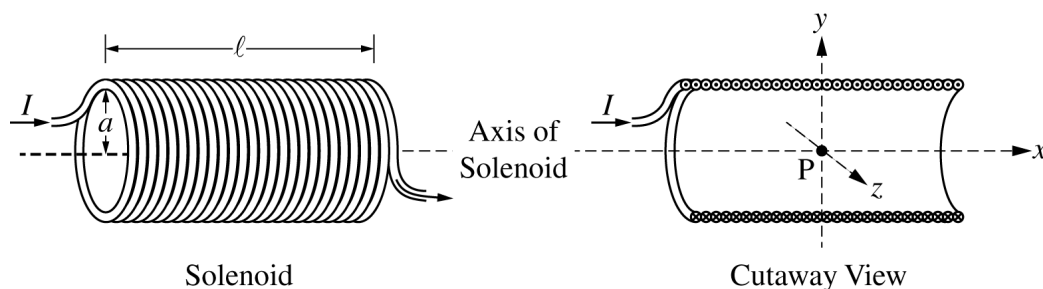
7.A: Make a scientific claim.

7.C: Support a claim with evidence from physical representations.

2019 SCORING GUIDELINES

Question 3

15 points



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 $\ell \gg a$.

- (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.

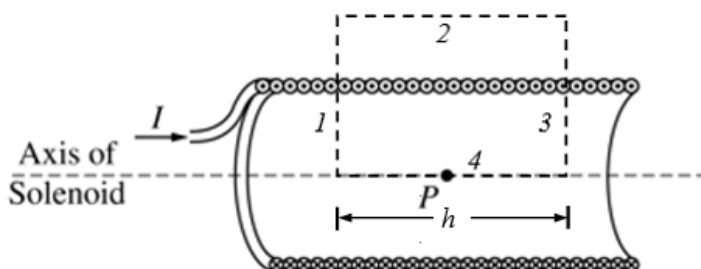
For choosing the “+ x -direction” and providing a justification	1 point
For a correct justification	1 point
Example: Using the right-hand rule for current on the left side of the solenoid, the fingers curl into the loop, so the magnetic field points to the right, or in the + x -direction.	
Example: Using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

2019 SCORING GUIDELINES

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.

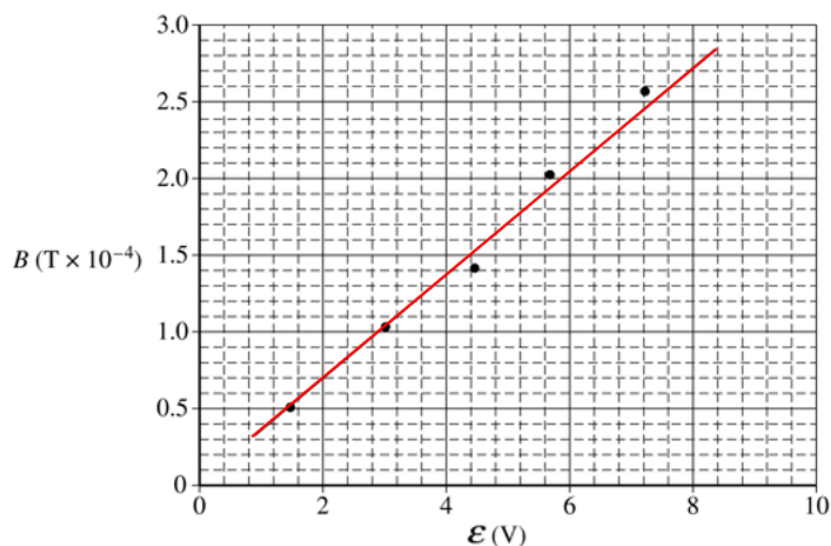
For using Ampere's law to calculate the magnetic field along the axis of the solenoid	1 point
$\int \mathbf{B} \cdot d\boldsymbol{\ell} = \mu_0 I_{enc} \therefore \left(\int \mathbf{B} \cdot d\boldsymbol{\ell} \right)_1 + \left(\int \mathbf{B} \cdot d\boldsymbol{\ell} \right)_2 + \left(\int \mathbf{B}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

2019 SCORING GUIDELINES**Question 3 (continued)**

- (c) LO CNV-8.C.c, SP 4.C
i. 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
$\text{slope} = \frac{\Delta y}{\Delta x} = \frac{(2.5 - 0.9)(\times 10^{-4} \text{ T})}{(6.4 - 2.0) \text{ V}} = 0.36 \times 10^{-4} = 3.6 \times 10^{-5} \text{ T/V}$	
For correctly giving the expression that relates the slope to the resistance of the solenoid	1 point
$B = \frac{\mu_0 N I}{\ell} = \frac{\mu_0 N \mathcal{E}}{\ell R} \therefore \text{slope} = \frac{\mu_0 N}{\ell R_S} \therefore R_S = \frac{\mu_0 N}{\ell \times \text{slope}}$ $R_S = \frac{(4\pi \times 10^{-7} \text{ (T}\cdot\text{m)/A})(100 \text{ turns})}{(0.40 \text{ m})(3.6 \times 10^{-5} \text{ T/V})} = 8.7 \Omega$	

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

2019 SCORING GUIDELINES**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.		
<i>Alternate Solution</i>	<i>Alternate Points</i>	
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 .		

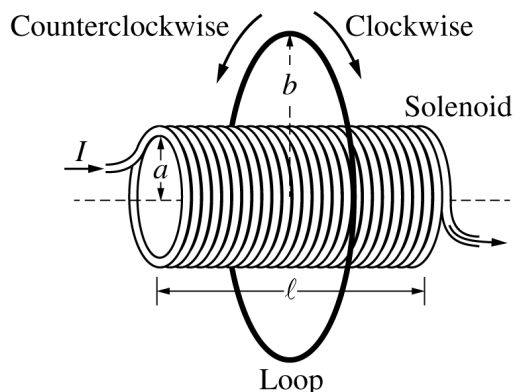
- ii. LO CNV-8.E.a, SP 2.E
1 point

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.		

2019 SCORING GUIDELINES**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.		

2019 SCORING GUIDELINES**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
$\mathcal{E} = \left \frac{d\Phi}{dt} \right = \frac{d(BA)}{dt} = A \frac{\Delta B}{\Delta t}$	
For using Ohm's law to calculate the current in the loop	1 point
$I_{\text{IND}} = \frac{V}{R} = \frac{A\Delta B/\Delta t}{R_L} = \frac{A\Delta B}{R_L\Delta t}$	
For using the correct radius for the area in the equation above	1 point
$I_{\text{IND}} = \frac{\pi a^2 \mu_0 N \Delta I / \ell}{R_L \Delta t} = \frac{\pi a^2 \mu_0 N I}{R_L \ell \Delta t}$	

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[®]** **CollegeBoard**

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

15 points total	Question	Distribution of ints
(a) i. 1 point		1 point
ii. 1 point		1 point
(b) i. 2 points	For using Gauss's law to calculate the electric flux	1 point
	$\Phi = \frac{Q}{\epsilon_0} = \frac{\rho V}{\epsilon_0}$	1 point
	For a correct answer	
	$\Phi = \frac{\rho_0 Ah}{\epsilon_0}$	
ii. 3 points	For correctly applying Gauss's law to the slab	1 point
	$\frac{Q}{\epsilon_0} = \oint \vec{E} \cdot d\vec{A} = EA_{top} + EA_{bottom}$	
	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
	$\frac{\rho_0 Ah}{\epsilon_0} = 2EA$	
	For correctly relating h to $2z$	1 point
	$\frac{\rho_0 A(2z)}{\epsilon_0} = 2EA$	
	$E = \frac{\rho_0 z}{\epsilon_0}$	

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

$$\frac{\sigma}{\epsilon_0} = -\frac{\rho_0 z_0}{\epsilon_0}$$

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

Substitute into equation above

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

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

1 point

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

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

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

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

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

For integrating with proper limits or constants of integration 1 point

$$\Delta V = \int_{z=0}^{z=0.005} \frac{\rho_0 z}{\epsilon_0} dz + \int_{z=0}^{z=0.005} \frac{\sigma}{\epsilon_0} dz$$

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

$$\Delta V = \frac{\rho_0}{\epsilon_0} \left[\frac{z^2}{2} \right]_{z=0}^{z=0.005} + \frac{\sigma}{\epsilon_0} [z]_{z=0}^{z=0.005} = \frac{\rho_0}{2\epsilon_0} (0.005^2 - 0) + \frac{\sigma}{\epsilon_0} (0.005 - 0)$$

$$\Delta V = \frac{\rho_0 z^2}{2\epsilon_0} + \frac{\sigma z}{\epsilon_0}$$

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

For a correct answer 1 point

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

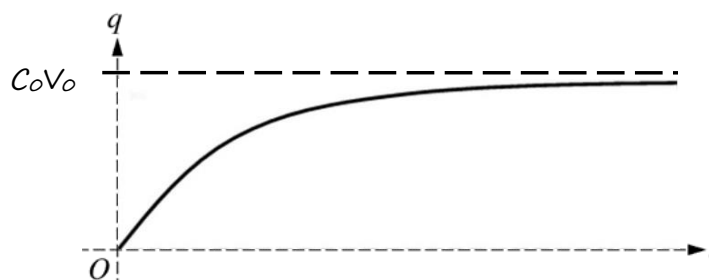
2017 SCORING GUIDELINES

Question

15 points total

Distribution
of points

(a) 3 points



For a concave down curve starting at the origin

1 point

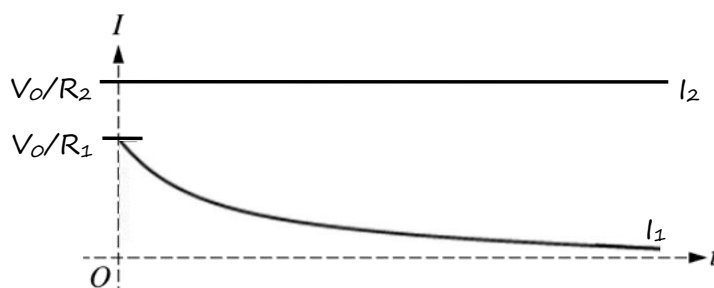
For a horizontal asymptote

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

$$V = IR$$

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

Substitute correct values into equation above

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

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

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

ii. 2 points

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

1 point

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

For correctly substituting into the equation above

1 point

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

Alternate Solution on next page.

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*

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

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

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

1 point

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

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

1 point

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

$$E = (-5.4 \times 10^{-5}) (e^{-\infty} - e^0) = 54 \, \mu\text{J}$$

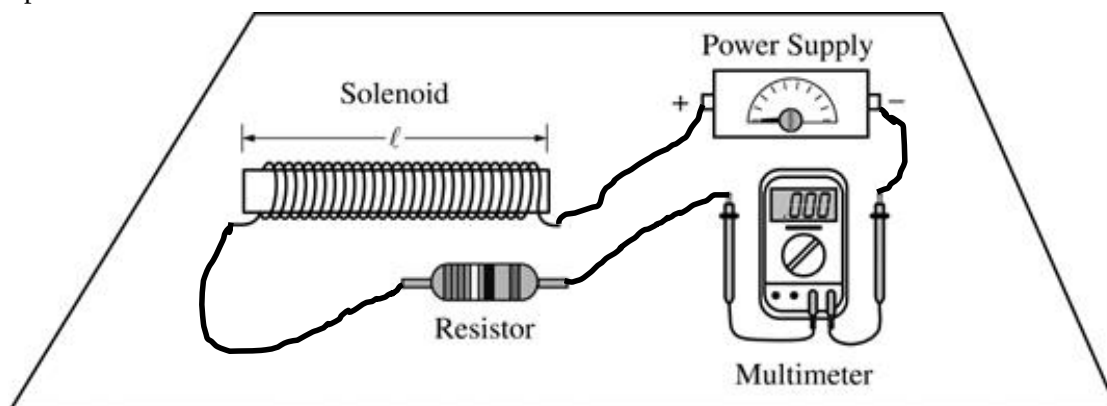
2017 SCORING GUIDELINES

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

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

For correctly relating the magnetic permeability of free space to the slope

1 point

$$\mu_0 = \text{slope}$$

For correct units

1 point

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

For Solenoid 2

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

ii. 1 point

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

1 point

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

For Solenoid 2

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

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.

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SCORING GUIDELINES

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

$$-V_1 = V_2$$

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

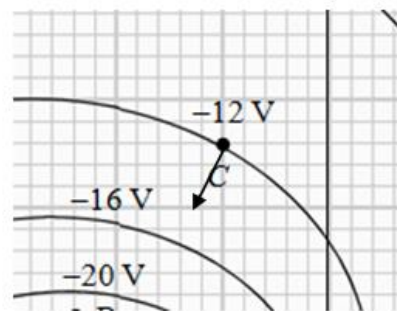
$$-\frac{q_1}{(5 \times 0.5\text{ m})} = \frac{(2.0 \text{ nC})}{(2 \times 0.5 \text{ m})}$$

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

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

$$|E| \approx \frac{\Delta V}{\Delta x}$$

For substituting values from the figure

1 point

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

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

SCORING GUIDELINES

Question 1 (continued)

Distribution
of points

2 points

For using a correct equation for the electric flux

1 point

$$\Phi_E = \frac{q_{enc}}{\epsilon_0}$$

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

For a correct answer with units

1 point

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

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

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

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

1 point

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

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

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

indicating the correct quantities for each axis

1 point

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

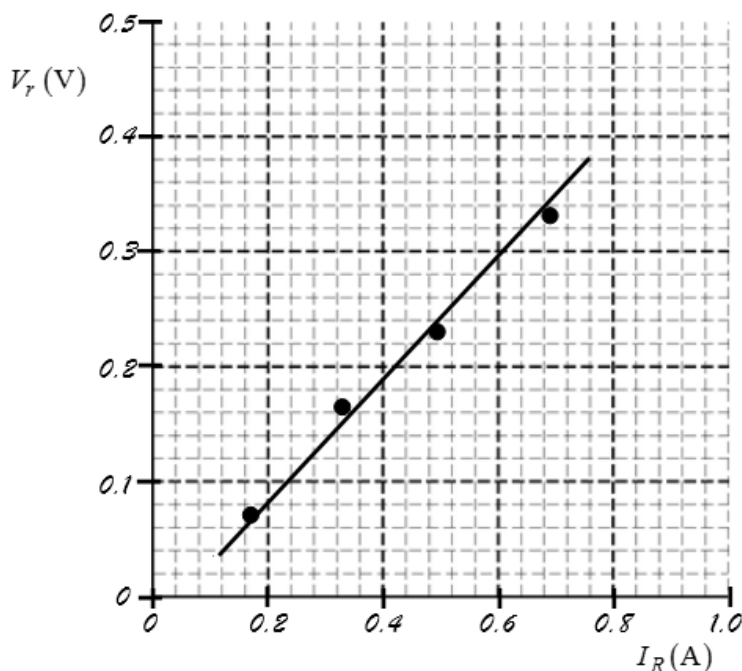
Note: Credit is received if the axes are reversed.

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

$$V_r = I_R r, \text{ therefore the slope equals } r$$

$$r = 0.526 \, \Omega$$

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

SCORING GUIDELINES

Question 2 (continued)

Distribution
of points

) 1 point

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

1 point

$$R = \frac{\rho L}{A} \quad \text{so} \quad \rho = \frac{AR}{L}$$

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

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

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

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.

SCORING 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

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

$$I = \mathcal{E}/R$$

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

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

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

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

Writing the acceleration as dv/dt

1 point

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

SCORING GUIDELINES

Question 3 (continued)

Distribution
of points

2 points

For setting the net force at terminal velocity equal to zero

1 point

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

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

in answer consistent with part (c)

1 point

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

(1 point

For a correct or consistent substitution in an appropriate power equation

1 point

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

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

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

*Alternate Solution**Alternate points**For a correct or consistent substitution in an appropriate power equation**1 point*

$$P = I^2 R$$

$$Mg = BIL$$

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

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

SCORING GUIDELINES

Question 3 (continued)

Distribution
of points

) 3 points

Using the equation from part (c)

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

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

For attempting separation of variables

1 point

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

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

1 point

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

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

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

For a correct answer

1 point

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

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