

Question 4: Qualitative Quantitative Translation (QQT)**8 points**

A	For indicating that $F_2 > F_1$	Point A1
	For correctly relating the magnitude of the magnetic force to the magnitude of the magnetic field	Point A2
	For indicating that the magnitude of the magnetic field at the location of Sphere 2 is greater than the magnitude of the magnetic field at the location of Sphere 1 by referring to either: - The relative distance from the spheres to Wires S and T - The direction of the magnetic fields from Wires S and T at the locations of the spheres	Point A3

Example Response

The magnitude of the magnetic force exerted on a sphere is directly proportional to Q , v , and B . Because Q and v are the same for both spheres, the difference in the magnitudes of the magnetic forces is due to the difference in the magnitudes of the magnetic fields at the locations of the spheres. The magnitude of the magnetic field is greater at the location of Sphere 2 than at the location of Sphere 1 because the fields from the wires are in the same direction. Therefore, $F_2 > F_1$.

B	For a multistep derivation that includes the equation $\oint \vec{B} \cdot d\vec{\ell} = \mu_0 I_{\text{enc}}$ or	Point B1
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$$d\vec{B} = \frac{\mu_0}{4\pi} \frac{I(d\vec{\ell} \times \hat{r})}{r^2}$$

Scoring Note: Vector notation is not required for this point to be earned. A multistep derivation that includes $B = \frac{\mu_0 I}{2\pi d}$ can earn this point.

	For a correct expression for the magnitude of the magnetic field due to the current in one wire at the location of Sphere 2	Point B2
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	For indicating that the magnitude of the total field is twice that due to one wire	Point B3
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Example Response

Determine the magnitude B of the magnetic field due to one wire.

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_0 I_{\text{enc}}$$

$$B(2\pi d) = \mu_0 I$$

$$B = \frac{\mu_0 I}{2\pi d}$$

Determine B_{tot} .

$$B_{\text{tot}} = \frac{\mu_0 I}{2\pi d} + \frac{\mu_0 I}{2\pi d}$$

$$B_{\text{tot}} = \frac{\mu_0 I}{\pi d}$$

C	For indicating $F_{\text{new}} = F_2$	Point C1
	For indicating $B_{\text{tot}} = \frac{3\mu_0 I}{2\pi d} - \frac{\mu_0 I}{2\pi d}$	Point C2
	OR	
	For indicating that the net magnitude of the magnetic field at the location of Sphere 2 will remain the same even though the field from Wire T will change	
	Example Response	
	The magnetic field at the location of Sphere 2 due to the current in Wire T is in the opposite direction to the magnetic field due to the current in Wire S. The current in Wire T is increased by a factor of 3. Therefore, $B_{\text{tot}} = \frac{3\mu_0 I}{2\pi d} - \frac{\mu_0 I}{2\pi d} = \frac{\mu_0 I}{\pi d}$ in this scenario. Thus, $F_{\text{new}} = F_2$.	

2019**AP** CollegeBoard

AP[®] Physics C: Electricity and Magnetism

Scoring Guidelines Set 1

2019 SCORING GUIDELINES

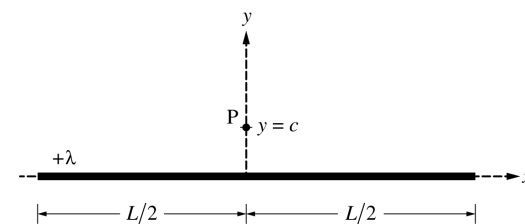
General Notes About 2019 AP Physics Scoring Guidelines

- 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.
- 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>.
- 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.
- 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 C: Mechanics*, *AP 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*.
- 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.
- 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

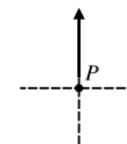


Note: Figure not drawn to scale.

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)
- 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
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- 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.	

2019 SCORING GUIDELINES

Question 1 (continued)

(a) continued

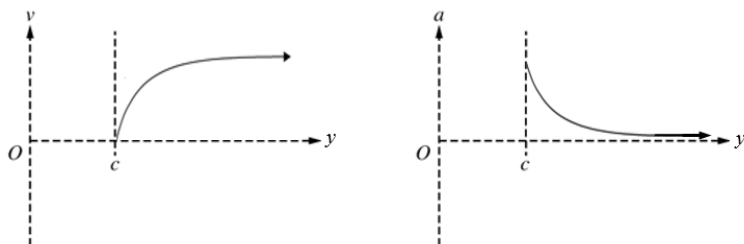
- iii. LO CNV-2.C, SP 5.A, 5.E
3 points

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.

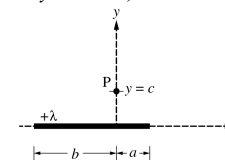


For a concave down graph for v as a function of position x that does not start at the origin	1 point
For a concave up graph for a as a function of position x that has an asymptote at the horizontal axis	1 point

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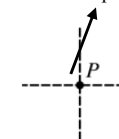
Question 1 (continued)

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?

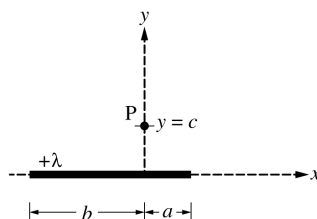
___ Yes ___ No

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.	

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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
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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

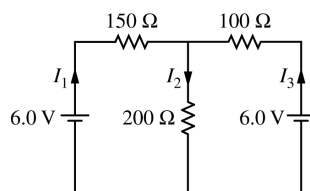


Figure 1

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)
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
$6 - 150I_1 - 200I_2 = 0$	
$6 - 100I_3 - 200I_2 = 0$	
$6 - 150I_1 + 100I_3 - 6 = 0$	
<u>Note:</u> 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 Ω 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
$-4.33I_2 = -.10 \therefore I_2 = 0.023 \text{ A}$	

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Question 2 (continued)

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

Calculate the power dissipated by the 200 Ω resistor.

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

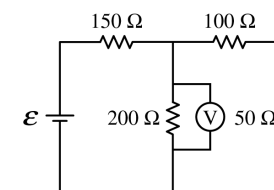


Figure 2

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

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

Calculate the current through the 50 Ω resistor.

For correctly calculating the equivalent resistance of the branch with the 50 Ω 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 Ω resistor	1 point
$I = \frac{V}{R} = \frac{(4.4 \text{ V})}{(100 \Omega + 50 \Omega)} \therefore I = 0.029 \text{ A}$	

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Question 2 (continued)

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

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

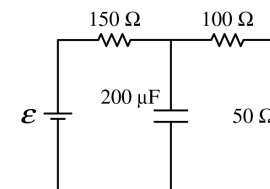
For using a correct equation to determine the current through the $150\ \Omega$ resistor	1 point
For correctly substituting the current from part (b) as I_3	1 point
$I_1 = I_2 + I_3 = \frac{(4.4\ \text{V})}{(200\ \Omega)} + 0.029\ \text{A} = 0.051\ \text{A}$	
For using a correct equation to determine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

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Question 2 (continued)

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

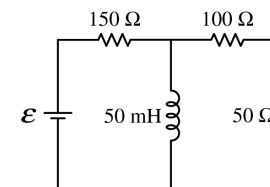
The $200\ \Omega$ resistor in the circuit in Figure 2 is replaced with a $200\ \mu\text{F}$ capacitor, as shown on the right, and the circuit is allowed to reach steady state. Calculate the current through the $50\ \Omega$ resistor.



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

- 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.

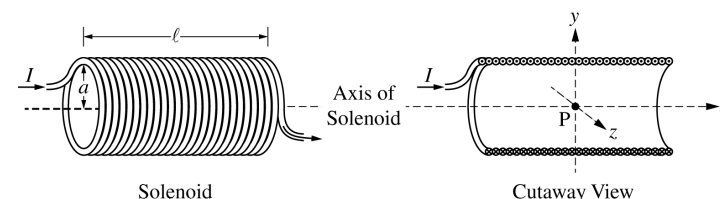
7.A: Make a scientific claim.

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.

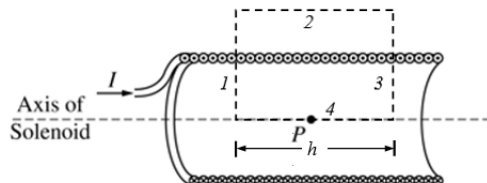
For choosing the “+ x -direction” and providing a justification	1 point
For a correct justification	1 point
Example: Using the right-hand rule for current on the left side of the solenoid, the fingers curl into the loop, so the magnetic field points to the right, or in the + x -direction.	
Example: Using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

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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
$\int \mathbf{B} \cdot d\boldsymbol{\ell} = \mu_0 I_{enc} \therefore \left(\int \mathbf{B} \cdot d\boldsymbol{\ell} \right)_1 + \left(\int \mathbf{B} \cdot d\boldsymbol{\ell} \right)_2 + \left(\int \mathbf{B} \cdot d\boldsymbol{\ell} \right)_3 + \left(\int \mathbf{B} \cdot d\boldsymbol{\ell} \right)_4 = \mu_0 I_{enc}$	
$\left(\int \mathbf{B} \cdot d\boldsymbol{\ell} \right)_1 + 0 + \left(- \int \mathbf{B} \cdot d\boldsymbol{\ell} \right)_1 + Bh = \mu_0 \frac{N}{\ell} hI$	
$Bh = \mu_0 \frac{N}{\ell} hI$	
For a correct answer	1 point
$B = \frac{\mu_0 NI}{\ell}$	

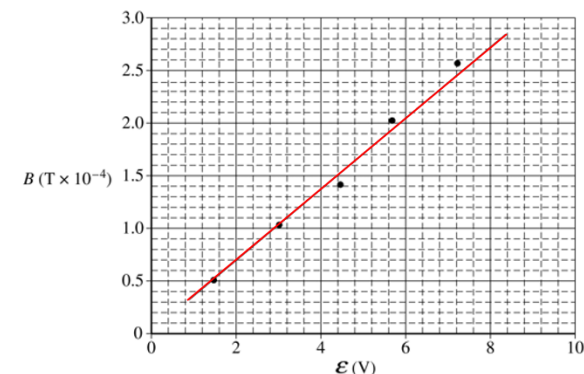
Some physics students conduct an experiment to determine the resistance R_S of a solenoid with radius $a = 0.015$ m, total turns $N = 100$, and total length $\ell = 0.40$ m. The students connect the solenoid to a variable power supply. A magnetic field sensor is used to measure the magnetic field strength 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.

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

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

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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 ?

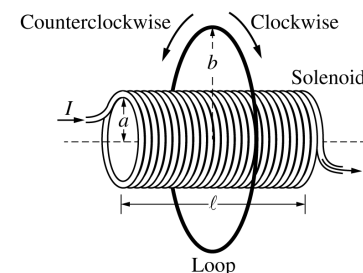
___ Yes ___ No

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.		

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.		

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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

- 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.
- 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>.
- 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.
- 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 C: Mechanics*, *AP 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*.
- 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.
- 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		
	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
	$\Phi = \frac{Q}{\epsilon_0} = \frac{\rho V}{\epsilon_0}$	
	For a correct answer	1 point
	$\Phi = \frac{\rho_0 Ah}{\epsilon_0}$	
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

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 $z_0 < 0$.

1 point

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

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

1 point

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

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

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

Substitute into equation above

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

1 point

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

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

1 point

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

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

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

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

For integrating with proper limits or constants of integration

1 point

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

1 point

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

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

1 point

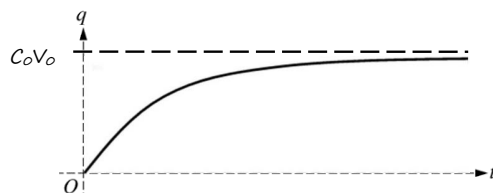
2017 SCORING GUIDELINES

Question

Distribution
of points

15 points total

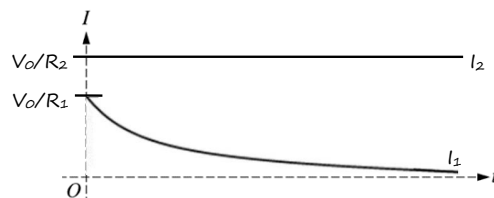
(a) 3 points



For a concave down curve starting at the origin
 For a horizontal asymptote
 For properly labeling the horizontal asymptote

1 point
 1 point
 1 point

(b) 4 points



For showing that I_2 is horizontal with the correct vertical intercept
 For showing that I_1 is concave up and asymptotic to $I = 0$
 For correctly labeling the vertical intercept of the I_1 graph
 For drawing the I_2 graph always above the I_1 graph

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

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.

1 point
 1 point

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

$$V = IR$$

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

Substitute correct values into equation above

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

For a correct answer

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

1 point

1 point

ii. 1 point

For a correct justification

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.

1 point

(e) i. 1 point

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

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

1 point

ii. 2 points

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

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

For correctly substituting into the equation above

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

1 point

1 point

Alternate Solution on next page.

2017 SCORING GUIDELINES

Question 2 (continued)

Distribution
of points

(e)(ii) continued

Alternate Solution

Alternate
PointsDerive 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

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

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

1 point

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

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

2017 SCORING GUIDELINES

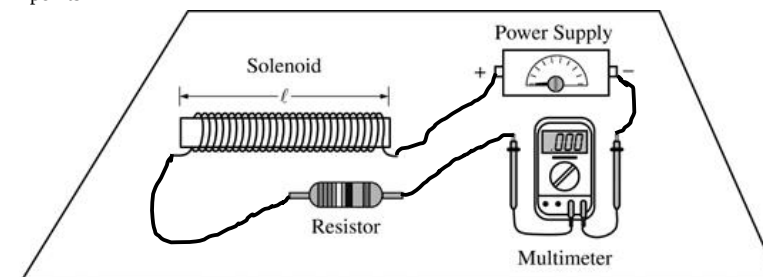
Question

Distribution
of points

15 points total

(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 permittivity 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

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

For Solenoid 2

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

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.