2017

AP CollegeBoard

AP Physics C: Electricity and Magnetism

Sample Student Responses and Scoring Commentary

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- ☑ Free Response Question 3
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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.

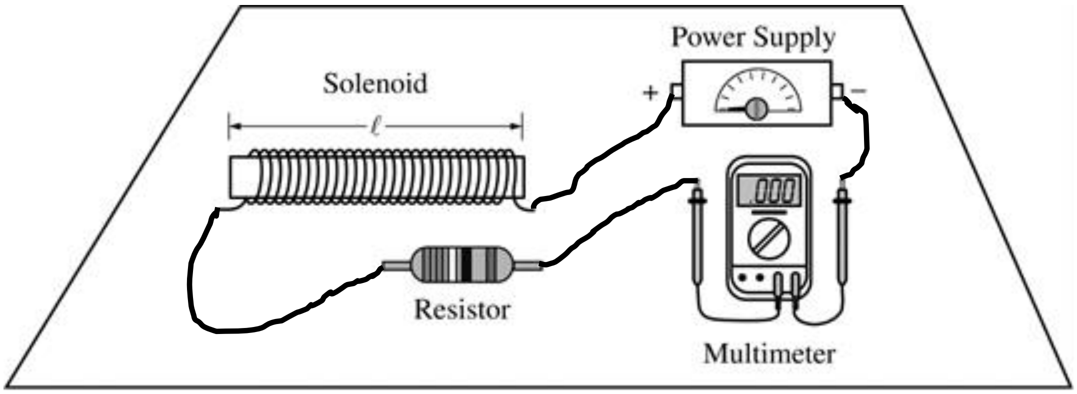
6. Strict rules regarding significant digits are usually not applied to numerical answers. However, in some cases answers containing too many digits may be penalized. In general, two to four significant digits are acceptable. Numerical answers that differ from the published answer due to differences 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.

Question 3

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.

Question 3 (continued)

Distribution of points

(b) 2 points

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

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

Examples:

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

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

(c)

i. 3 points

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

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

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

$\mu_0 = \text{slope}$

For correct units — 1 point

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

For Solenoid 2

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

ii. 1 point

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

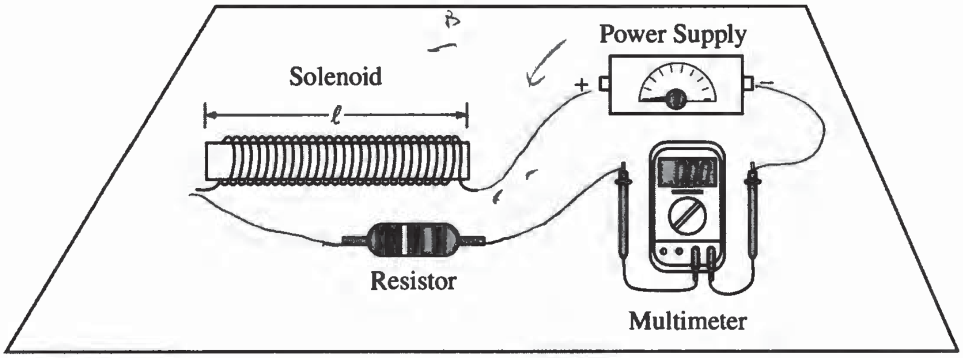
$$\%\ \text{error} = \frac{|\text{acc} - \text{exp}|}{\text{acc}}\times 100\% = \frac{\left|\left(1.26\times 10^{-6}\right) - \left(1.18\times 10^{-6}\right)\right|}{\left(1.26\times 10^{-6}\right)}\times 100\% = 6.35\%$$

For Solenoid 2

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

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.	



3. When studying Ampere's law, students collect data on the magnetic field of two different solenoids in order to determine the magnetic permeability of free space μ_0. The solenoids are created by wrapping wire around a hollow plastic tube. The solenoids of length ℓ with N turns of wire will be connected in series to a power supply and resistor. A multimeter will be used as an ammeter to measure the magnitude of the current I through the solenoids. The main components for the setup with one of the solenoids are shown in the figure above.

(a)

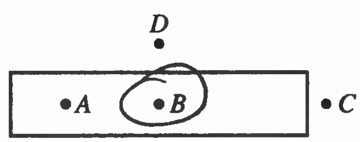
i. On the figure above, draw wire connections between the solenoid, power supply, resistor, and multimeter that will complete the circuit and allow students to measure the magnitude of the current through the solenoid.

ii. Using the connections you made in part (a)i above, what will be the direction of the magnetic field inside the solenoid?

____ Toward the top of the page   ✓ To the left   ____ Out of the page

____ Toward the bottom of the page   ____ To the right   ____ Into the page

The rectangle shown below represents the solenoid (the loops of wire are not shown). Points A, B, and ~~C are along the~~ central axis of the solenoid with point B at the middle of the solenoid. Point D is directly above point B.



iii. From the choices below, select the point where you would place a magnetic field probe (a probe that can measure the magnitude of the magnetic field) to best measure the strength of the magnetic field of the solenoid in order to determine the magnetic permeability of free space μ_0.

____ A ✓ B ____ C ____ D

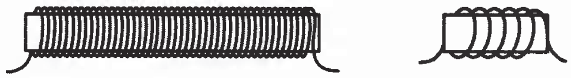
Justify your answer based on the model for a simple solenoid.

-b/c, should not place probe at D because there is no magnetic field outside. Placing probe at A or C causes the measurement to be at the edge, which does not reflect true B field inside solenoid. Point B is the best option b/c it is inside the solenoid, in the middle, and away from edge

Question 3 continues on the next 2 pages

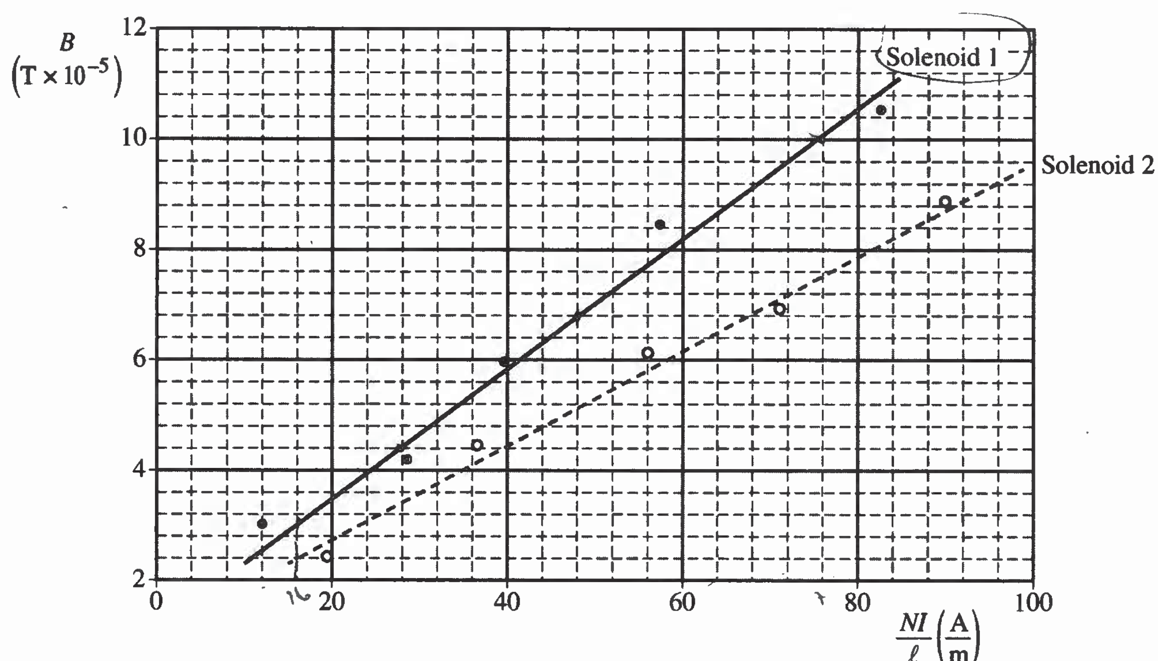
GO ON TO THE NEXT PAGE.

The figures below show two different solenoids that will be connected in the circuit above. Solenoid 1 has a length $\ell = 25$ cm with $N = 100$ turns. Solenoid 2 has a length $\ell = 5.0$ cm with $N = 5$ turns.



Note: Figures not drawn to scale.

A graph of the magnitude of the magnetic field B as a function of NI/ℓ is shown below. The best-fit lines for the data are shown as a solid line for solenoid 1 and as a dashed line for solenoid 2.



$\mu_0 n I$

(b) Which solenoid's best-fit line would give the best results for determining a value for the magnetic permeability of free space μ_0?

✓ Solenoid 1 ____ Solenoid 2

Justify your answer.

Solenoid 1 gives the most accurate results when the wire turns are close to one another, and solenoid length is relatively long. To ensure that these conditions are met, solenoid 1 should be selected.

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(c)

i. Use the slope of the best-fit line for the solenoid chosen in part (b) to calculate the magnetic permeability of free space μ_0.

$B_{solenoid} = \frac{\mu_0 N I}{\ell}$

Slope of the line gives μ_0

Points chosen on the line: (16, 3) and (76, 10)

$m = \frac{7}{60} = 0.12$ Take into account 10^{-5}

$\Rightarrow \mu_0 = 0.12 \times 10^{-5} = 1.2 \times 10^{-6}$

ii. Calculate the percent error for the experimental value of the magnetic permeability of free space μ_0 determined in part (c)i.

$$\left| \frac{(7 \times 10^{-6}) - (4\pi \times 10^{-7})}{4\pi \times 10^{-7}} (100)\% \right| = 4.5\%$$

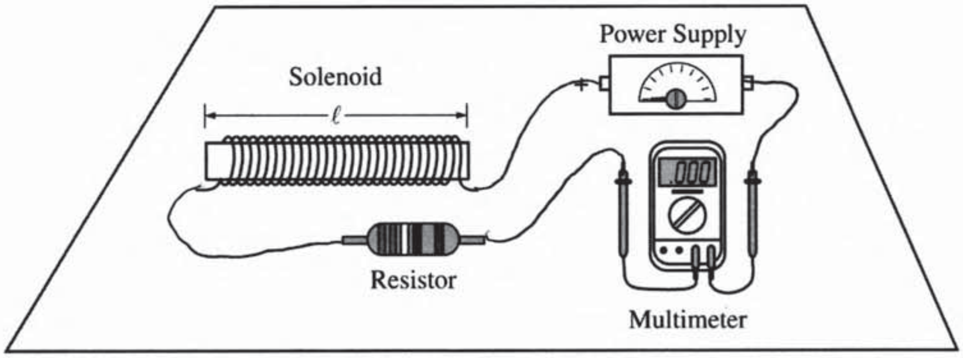
(d)

i. What is a reasonable physical explanation for a best-fit line that does not pass through the origin?

The magnetic field is zero even with some current running through. This can be caused by the resistance already existed in the circuit, which reduces current flow initially to almost 0

ii. Suppose a student connects the solenoid in a closed circuit similar to the circuit in part (a)i but without the resistor. The student notices the ~~multimeter~~ stops functioning after the power supply is turned on. Explain what causes the failure of the multimeter.

Without resistor, the current that runs through is excessively high. Since the multimeter only measures current up to a maximum value, it will not be able to measure this current and stops functioning.



3. When studying Ampere's law, students collect data on the magnetic field of two different solenoids in order to determine the magnetic permeability of free space μ_0. The solenoids are created by wrapping wire around a hollow plastic tube. The solenoids of length ℓ with N turns of wire will be connected in series to a power supply and resistor. A multimeter will be used as an ammeter to measure the magnitude of the current I through the solenoids. The main components for the setup with one of the solenoids are shown in the figure above.

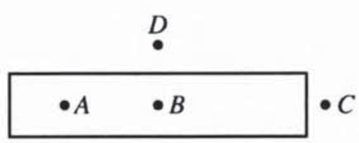
(a)

i. On the figure above, draw wire connections between the solenoid, power supply, resistor, and multimeter that will complete the circuit and allow students to measure the magnitude of the current through the solenoid.

ii. Using the connections you made in part (a)i above, what will be the direction of the magnetic field inside the solenoid?

____ Toward the top of the page	_✓_ To the left	____ Out of the page
____ Toward the bottom of the page	____ To the right	____ Into the page

The rectangle shown below represents the solenoid (the loops of wire are not shown). Points A, B, and C are along the central axis of the solenoid with point B at the middle of the solenoid. Point D is directly above point B.



iii. From the choices below, select the point where you would place a magnetic field probe (a probe that can measure the magnitude of the magnetic field) to best measure the strength of the magnetic field of the solenoid in order to determine the magnetic permeability of free space μ_0.

____ A _✓_ B ____ C ____ D

Justify your answer based on the model for a simple solenoid.

It should definitely be inside the solenoid (not C or D) to measure the field. It should be in the middle of the solenoid so that the edges of the solenoid on the left and right have minimal effect.

Question 3 continues on the next 2 pages

GO ON TO THE NEXT PAGE.

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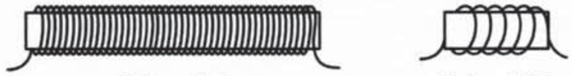
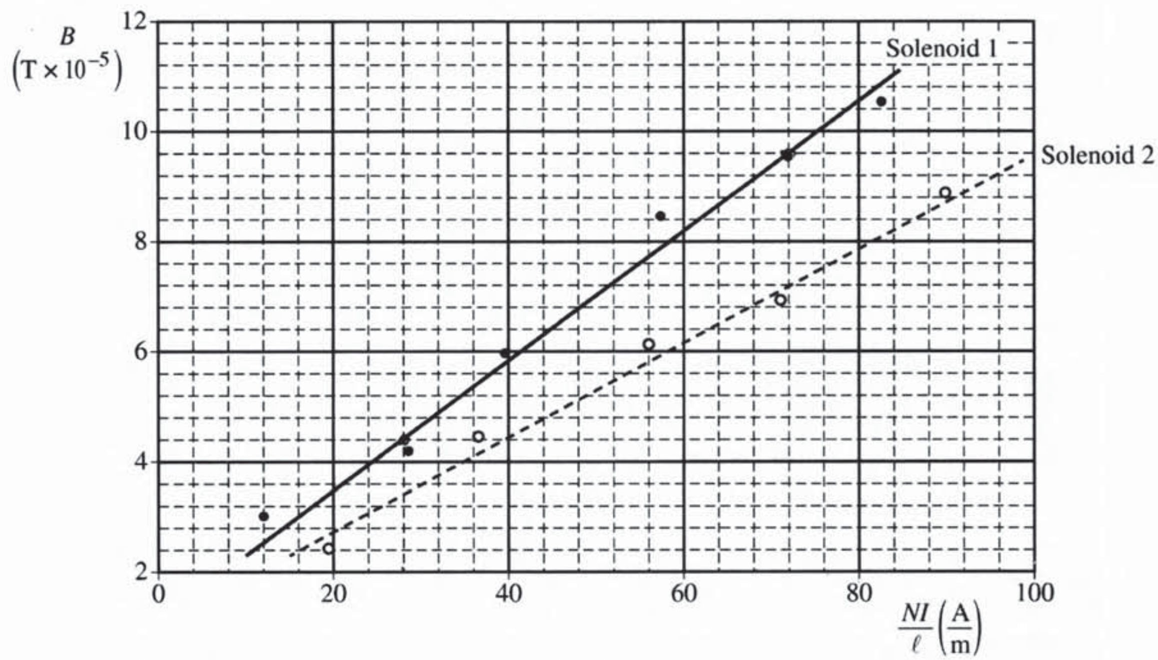


Solenoid 1   Solenoid 2

Note: Figures not drawn to scale.

A graph of the magnitude of the magnetic field B as a function of NI/ℓ is shown below. The best-fit lines for the data are shown as a solid line for solenoid 1 and as a dashed line for solenoid 2.



(b) Which solenoid's best-fit line would give the best results for determining a value for the magnetic permeability of free space μ_0?

✔ Solenoid 1 ____ Solenoid 2

Justify your answer.

It is closer to an ideal solenoid since it has more loops that are closer together. 1 has 4 loops per centimeter while 2 only has 1 loop per centimeter.

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(c)

i. Use the slope of the best-fit line for the solenoid chosen in part (b) to calculate the magnetic permeability of free space μ_0.

$B = \mu_0 n I$

$\mu_0 = \frac{B}{nI}$ $\mu_0 = \frac{B}{\frac{NI}{\ell}}$ = slope of best fit line

$n = \frac{N}{\ell}$

Points:
(28, 4.4)
(72, 9.6)

$\frac{9.6-4.4}{72-28} = .118182 \frac{T \cdot m}{A}$

ii. Calculate the percent error for the experimental value of the magnetic permeability of free space μ_0 determined in part (c)i.

$\frac{.118182 - \mu_0}{\mu_0} \times 100$

$\mu_0 = 4\pi \times 10^{-7}$

$94045 \times 100 = 9404500\%$

(d)

i. What is a reasonable physical explanation for a best-fit line that does not pass through the origin?

Since the solenoid is not ideal and has fewer coils then it cannot produce perfect data.

ii. Suppose a student connects the solenoid in a closed circuit similar to the circuit in part (a)i but without the resistor. The student notices the multimeter stops functioning after the power supply is turned on. Explain what causes the failure of the multimeter.

~~the student shorted the circuit because~~

The multimeter cannot handle too large of a current. The circuit requires a resistor to lower the current so it all doesn't go into the multimeter which causes the malfunction.

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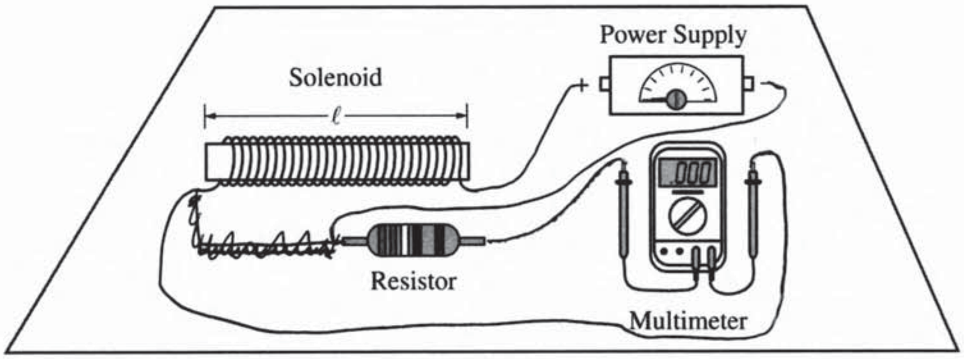

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(a)

i. On the figure above, draw wire connections between the solenoid, power supply, resistor, and multimeter that will complete the circuit and allow students to measure the magnitude of the current through the solenoid.

ii. Using the connections you made in part (a)i above, what will be the direction of the magnetic field inside the solenoid?

____ Toward the top of the page	_____ To the left	_✓_ Out of the page
____ Toward the bottom of the page	_____ To the right	____ Into the page

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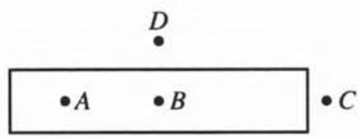


iii. From the choices below, select the point where you would place a magnetic field probe (a probe that can measure the magnitude of the magnetic field) to best measure the strength of the magnetic field of the solenoid in order to determine the magnetic permeability of free space μ_0.

____ A _✓_ B ____ C ____ D

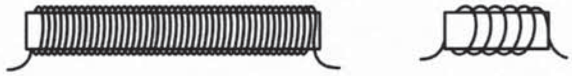
Justify your answer based on the model for a simple solenoid.

The magnetic fields of solenoids point towards the center.

Question 3 continues on the next 2 pages

GO ON TO THE NEXT PAGE.

The figures below show two different solenoids that will be connected in the circuit above. Solenoid 1 has a length $\ell = 25$ cm with $N = 100$ turns. Solenoid 2 has a length $\ell = 5.0$ cm with $N = 5$ turns.



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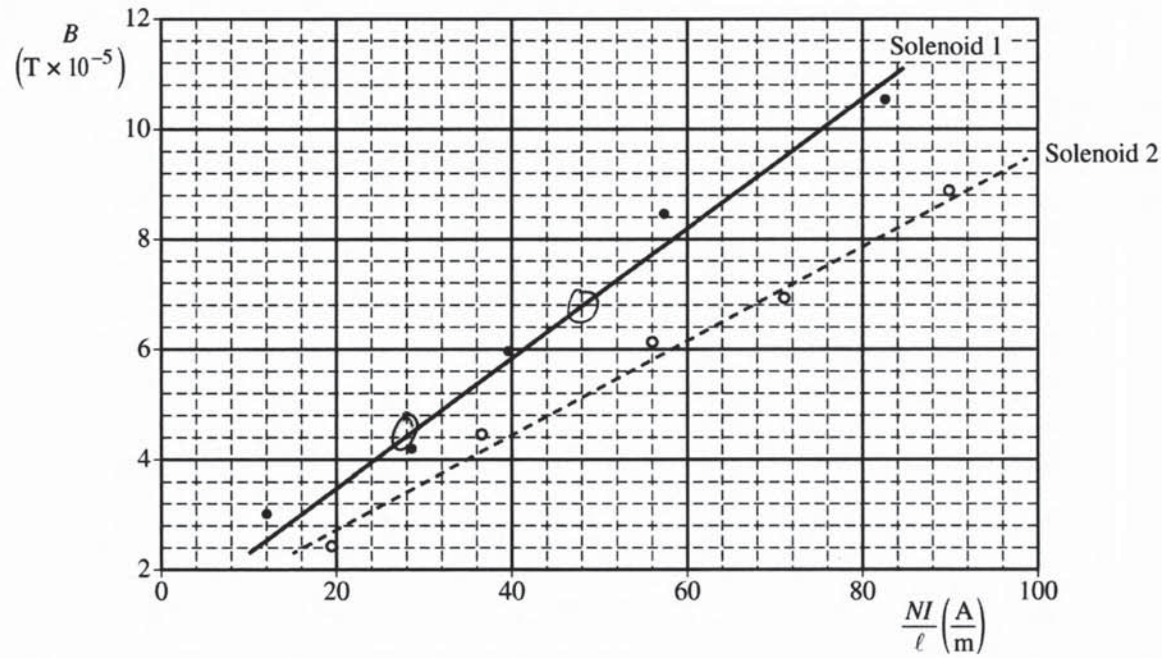

(b) Which solenoid's best-fit line would give the best results for determining a value for the magnetic permeability of free space μ_0?

_✓_ Solenoid 1 ____ Solenoid 2

Justify your answer.

The greater amount of coils, the stronger the magnetic field.

~~B =~~ $B = \mu_0 n I$

(c)

i. Use the slope of the best-fit line for the solenoid chosen in part (b) to calculate the magnetic permeability of free space μ_0.

$$\mu_0 = \frac{6.8 - 4.4}{48 - 28} = 0.12$$

ii. Calculate the percent error for the experimental value of the magnetic permeability of free space μ_0 determined in part (c)i.

~~$B = \mu_0 n I$~~ ~~$B = \mu_0 n I$~~ ~~$F = I l \times B$~~

~~$B =$~~ $\mu_0 I = \oint B \cdot ds$

(d)

i. What is a reasonable physical explanation for a best-fit line that does not pass through the origin?

The resistor dissipates the energy into heat.

ii. Suppose a student connects the solenoid in a closed circuit similar to the circuit in part (a)i but without the resistor. The student notices the multimeter stops functioning after the power supply is turned on. Explain what causes the failure of the multimeter.

The multimeter short circuits because of the magnetic field created by large amount of coils.

Question 3

Overview

The responses to this question were expected to demonstrate the following:

- How to use a multimeter to measure current in a circuit.
- An understanding of the magnetic properties of an ideal solenoid, as well as the properties of a real solenoid that best enable it to approximate the ideal.
- An understanding of how coil density and aspect ratio are invoked when using The Law of Biot & Savart to determine the value of magnetic field of an ideal solenoid.
- An understanding that real solenoids experience nonzero magnetic fields outside of the coils, as well as edge effects at the ends.
- An understanding that trendlines should be used rather than the data points from which they are formed in determining physical values from data.
- An understanding of how to compare measured and expected values using percent difference.
- An understanding that key physical values can be determined from graphs and how to extract those values.
- An understanding that the Earth's magnetic field can affect measurements of magnetic field strength; no experiment is in complete isolation from its surroundings. An understanding that real solenoids have a nonzero resistance that is very small.

Sample: E&M Q3 A
Score: 11

Parts (a) and (b) earned full credit. In part (a)(i) all of the circuit components are connected in series, including the multimeter. Part (a)(ii) has the correct selection consistent with the connections in part (a)(i). Part (a)(iii) has the correct selection and discusses both the strength outside the solenoid and edge effects. Part (b) has a correct selection and discusses both coil density and length. Part (c)(i) correctly calculates the slope from the line and not data points and relates the slope to the permeability, but does not include the units, so 2 points were earned. Part (c)(ii) has an incorrect value for the measured value, so no credit was earned. Part (d)(i) does not mention extraneous fields, so no credit was earned. Part (d)(ii) discusses excessively high current, but does not discuss the resistance of the solenoid/circuit, so 1 point was earned.

Sample: E&M Q3 B
Score: 10

Parts (a)(i) and (a)(ii) earned full credit. Part (a)(iii) has a correct selection and discusses edge effects but does not mention the field strength, so 2 points were earned. Part (b) discusses the loops but not the length, so 1 point was earned. Part (c)(i) correctly relates the slope to the permeability constant and has correct units, but it does not include $\times 10^{-5}$ in the values from the vertical scale and, thus, the answer is incorrect and 2 points were earned. In part (c)(ii) the answer is unreasonably high, but it is consistent with the incorrect answer in part (c)(i), so full credit was still earned. Part (d)(i) does not mention extraneous fields, so no credit was earned. Part (d)(ii) discusses excessively high current, but does not sufficiently discuss the resistance of the solenoid/circuit, so 1 point was earned.

Question 3 (continued)

Sample: E&M Q3 C
Score: 5

Part (a)(i) earned full credit. Part (a)(ii) is inconsistent with part (a)(i), so no credit was earned. Part (a)(iii) has a correct selection and attempts a justification, but the justification is incorrect, so 1 point was earned. Part (b) discusses the loops but not the length, so 1 point was earned. Part (c)(i) correctly relates the slope to the permeability constant but has incorrect units and does not include $\times 10^{-5}$ in the values from the vertical scale; therefore, the answer is incorrect, so 1 point was earned. Part (c)(ii) does not calculate percent error, so no credit was earned. Part (d)(i) does not mention extraneous fields, so no credit was earned. Part (d)(ii) does not discuss excessively high current or the resistance of the solenoid/circuit, so no credit was earned.