Chief Reader Report on Student Responses:

2019 AP® Physics C Electricity & Magnetism Free-Response Questions

Set 1

• Number of Students Scored	25,342		
• Number of Readers	377 (for all Physics exams)		
• Score Distribution	Exam Score	N	%At
	5	9,532	37.6
	4	5,725	22.6
	3	3,230	12.7
	2	4,212	16.6
	1	2,643	10.4
• Global Mean	3.60		

The following comments on the 2019 free-response questions for AP® Physics C Electricity & Magnetism were written by the Chief Reader, Shannon Willoughby, Montana State University. They give an overview of each free-response question and of how students performed on the question, including typical student errors. General comments regarding the skills and content that students frequently have the most problems with are included. Some suggestions for improving student preparation in these areas are also provided. Teachers are encouraged to attend a College Board workshop to learn strategies for improving student performance in specific areas.

Question #1 **Task:** Apply Gauss' law **Topic :** Linear charge distribution

Max. Points: 15 **Mean Score:** 6.51

What were the responses to this question expected to demonstrate?

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

- An understanding of the properties of the electric field due to a charge distribution
- The ability to use Gauss's law
- The ability to identify an appropriate Gaussian surface
- The ability to graphically describe the motion of a charged particle in an electric field
- An understanding of when Gauss's law is an appropriate approach to solve a problem
- The ability to separate a vector into components
- The ability to carry out integration along a line

How well did the responses address the course content related to this question? How well did the responses integrate the skills required on this question?

- The question required students to draw an electric field vector in the vicinity of a linear charge distribution that could be approximated as infinite.
- The question required students to describe the appropriate Gaussian surface for this charge distribution.
- The question required students to write out Gauss's Law and plug in the appropriate components to solve for the electric field at a given point.
- The question required students to sketch the graphs of velocity vs. position and acceleration vs. position for a charged particle placed in the field.
- The question required students to draw an electric field vector for a new charge distribution that was still linear but could not be approximated as infinite.
- The question required students to state whether or not Gauss's Law was appropriate for the new charge distribution and give the reasoning.
- The question required students to identify mistakes in given integrals and state the necessary correction.

What common student misconceptions or gaps in knowledge were seen in the responses to this question?

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Many students thought a Gaussian surface must completely surround a charge distribution.	• The Gaussian surface was a cylinder of radius c coaxial with the line of charge, but much shorter than the line of charge.
• Students often confused line integrals and surface integrals.	• Gauss's Law involves a surface integral, which when carried out properly for this problem should give the area of the side of a cylinder.

• Students often confused linear, surface, and volume charge densities.	• The linear charge density is charge per length, Q/L.
• Many students had difficulty graphically conveying the relationship between velocity and position.	• When the charge is released from rest at y=c, the line representing the motion starts at (0,c) on the velocity vs position graph.
• Many students did not fully understand the requirements for a Gaussian surface.	• The Gaussian surface is chosen such that the electric field over the surface to be integrated is a constant and that the electric field vector and area vector are either parallel or perpendicular, simplifying the dot product in Gauss's Law.
• Many students confused integrating the y-components of the electric field over a line charge in the x-direction with integrating along the y-direction.	• The line charge is along the x-axis: Therefore the integration of the y-components of the electric field is carried out with respect to x.

What resources would you recommend to teachers to better prepare their students for the content and skill(s) required on this question?

- AP Physics C teachers can find useful resources on the Course Audit webpage and the AP Central Home Page for AP Physics C. In addition, topic questions that are tied to specific learning objectives and science practices can be found on the new AP Classroom.
- The new AP Physics 1 Student Workbook contains many helpful scenarios which address topics and skills also covered in AP Physics C. These scenarios can be modified or scaffolded for Physics C students.
- The AP Physics Online Teacher Community is active, and there are many discussions concerning teaching tips, techniques, and activities that AP Physics teachers have found helpful. It is easy to sign up and you can search topics of discussions from all previous years.
- New teachers (and career changers) might want to consider signing up for an APSI. An APSI is a great way to get in-depth teaching knowledge on the AP Physics curriculum and exam, as well as network with colleagues from around the country.

Question #2 **Task:** Circuit analysis **Topic:** Complex Circuits

Max. Points: 15 **Mean Score:** 7.53

What were the responses to this question expected to demonstrate?

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

- Derive a correct junction equation and at least two loop equations for a circuit with multiple sources of emf, paying attention to and using clear subscripts that were specified in the problem
- Use appropriate algebra skills to solve simultaneous equations with multiple unknowns
- Derive an expression to calculate the power dissipated by a specific resistor
- Solve for the current of any resistor and the voltage of a battery in a circuit with known resistors and a single source of emf
- Determine the total current in a circuit with multiple known resistors, a single source of emf, and a capacitor at steady state
- Recognize the effect of an inductor at steady state on a circuit with multiple known resistors with various types of connections

How well did the responses address the course content related to this question? How well did the responses integrate the skills required on this question?

- A large majority of students were correctly able to generate equations using Kirchhoff's rules for part ai.

- Approximately half the students recognized the need to use a form of the power equation not on the formula sheet: $P = I^2R$ versus $P = IV$ in part aiii.

- Most students were correctly able to simplify the second circuit down to a correct equivalent resistance and used this value to solve for the emf of the battery (correctly recognizing series and parallel connections) in parts b and c.

- A large majority of students correctly recognized that the capacitor in steady state has no current travelling through it, and the resistors were connected in series with each other and the battery in part di.

- A large majority of students recognized that the current in the 50 Ω resistor with the inductor at steady state would receive less current in part diii.

What common student misconceptions or gaps in knowledge were seen in the responses to this question?

- More than half of the students were not able to use correct algebra skills to solve the simultaneous equations to obtain the current across the 200 Ω resistor in part aii.

- Students only including final answers in work area, however, writing "scratch" work all along the edge of the page.

- Several students solved for the voltage across the 50 Ω resistor rather than the current in part b.

- Students are not clearly showing their problem solving process in their work, which makes it difficult and time consuming to follow/grade.

- Many students included extraneous work – solving for quantities that were not necessary.

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Students not familiar with circuits including multiple sources for emf/with Kirchhoff's Rules: $6\ V = I_1 150\ \Omega$, $6\ V = I_2 200\ \Omega$, $6\ V = I_3 100\ \Omega$, $12\ V = I_1 150\ \Omega + I_2 200\ \Omega + I_3 100\ \Omega$.	• Junction Rule: $I_2 = I_1 + I_3$ • Loop #1: $6 - 150I_1 - 200I_2 = 0$ • Loop #2: $6 - 100I_3 - 200I_2 = 0$ • Loop #3: $6 - 150I_1 + 100I_3 - 6 = 0$
• Students not able to solve a system of equations – either by hand or properly with their calculators	• Many students used matrices to solve.
• Students are not showing enough/any work for questions asking them to calculate: ex. $P = I^2R = 0.11\ W$ $R_{eq} = 237\ \Omega$, $\varepsilon = IR = 12.1\ V$	• When asked to calculate a value, students must show their work each step of the way. • Students were allowed to consolidate their work into one step that still included all work: $\varepsilon = (\frac{4.4}{200} + 0.029)(150\ \Omega + ((200\ \Omega)^{-1} + (100\ \Omega + 50\ \Omega)^{-1})^{-1})$ $= 12.1\ \text{V}$
• Students incorrectly assuming the current through the 200 Ω resistor was the same as the 50 Ω resistor	• $I_{50} = \frac{4.4}{100+50} = 0.029\ A$
• Students not carefully noting in their work whether they were referring to the sum of the 100 Ω and 50 Ω resistors or the 150 Ω resistor ex. $I = \frac{4.4}{150} = 0.0293\ A$	• See above example

• Students using proportionalities to solve for the current in the 50 Ω resistor and the voltage of the battery, but not clearly showing how those proportionalities came about ex. $(4.4\text{ V})/3 = 1.47\text{ V}$, $I_{50} = \frac{1.47\text{ V}}{50\ \Omega} = 0.0293A$	• Students need to state clearly or show how the 1/3rd came about: $\frac{50}{100+50} = \frac{1}{3}$, so the 50 Ω resistor has 1/3rd the voltage across the branch. Then they can solve for the current. • Similar work in regard to solving for the voltage of the battery
• Students not clearly justifying their choice in regards to the current in the 50 Ω resistor with the inductor at steady state (ie. "It's now a wire," "The inductor will take all the current")	• "The inductor is now like a wire with zero resistance, so no current will flow through the 50 Ω resistor." • "The inductor is now a wire and creates a short circuit, so no current will flow through the 50 Ω resistor."

Based on your experience at the AP® Reading with student responses, what advice would you offer teachers to help them improve the student performance on the exam?

- AP Physics C students must be familiar with circuits, including multiple sources of emf, and how to apply Kirchhoff's rules to those circuits.

- Students need to practice working with solving simultaneous equations using clear notation consistently.

- Students should be familiar with the difference between the terms "determine" and "calculate" and teachers need to use the same level of scrutiny on their own classroom assessments. Teachers must require that students show all their work and students must not assume that readers will "know" what they meant.

What resources would you recommend to teachers to better prepare their students for the content and skill(s) required on this question?

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Question #3 **Task:** Apply Ampere's Law **Topic :** Solenoids

Max. Points: 15 **Mean Score:** 4.39

What were the responses to this question expected to demonstrate?

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

- An understanding of the relationship between current and the magnetic field in a solenoid
- The ability to identify an appropriate Amperian loop
- The ability to use Ampere's law
- An understanding of the meaning of the slope of a best-fit line
- An understanding of the meaning of the *y*-intercept of a best-fit line
- The ability to use Faraday's law to determine induced current
- An understanding of Lenz's law

How well did the responses address the course content related to this question? How well did the responses integrate the skills required on this question?

- The question required students to state the direction of the magnetic field inside a solenoid and explain how the direction was determined.
- The question required students to draw the appropriate Amperian loop for the solenoid.
- The question required students to use Ampere's Law to derive an expression for the magnetic field inside the solenoid.
- The question required students to draw a best-fit line on a graph containing plotted data points.
- The question required students to use the slope of the best-fit line, along with the expression derived from Ampere's Law, to calculate the resistance of the solenoid.
- The question required students to understand that the presence of a non-zero y-intercept indicated that an additional magnetic field was present.
- The question required students to understand that the additional magnetic field had no effect on the slope of the line, and therefore no effect on the calculation of the resistance of the solenoid.
- The question required students to apply Lenz's Law to determine the direction of induced current in a loop around the solenoid as the current changed.
- The question required students to use Faraday's Law to derive an expression for the induced current in the loop.

What common student misconceptions or gaps in knowledge were seen in the responses to this question?

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Many students could not explain the Right Hand Rule.	• When the current in a looped wire is going in a clockwise direction, as looking from the left-hand side, the magnetic field is generated into the loop as per the right hand rule.
• Some students referenced the coils of the wire instead of the direction of the current.	• When the current in a looped wire is going in a clockwise direction, as looking from the left-hand side, the magnetic field is

	generated into the loop as per the right hand rule.
• Most students could not draw the Amperian loop for a solenoid.	• A rectangular loop shorter than the length of the solenoid that contained currents in either the top or bottom of the solenoid, with the inner edge of the loop along the center of the solenoid
• Some students confused line integrals with surface integrals.	• Integrating along the entire loop, with the result of the integration being the length of the loop inside the solenoid
• Many students had difficulty drawing a best fit line properly.	• A straight line that passed through the data points such that about the same number of data points were above the line as below
• Many students did not understand that the expression derived from Ampere's Law should correspond to the best fit line on the graph.	• The slope of the best fit line corresponds to the expression from Ampere's Law, and therefore can be used to calculate the resistance of the solenoid.
• Many students did not calculate the slope of the line correctly.	• The slope should be calculated using two points on the line, and should be calculated to the correct **scale** from the axes.
• Many students did not understand that the presence of earth's magnetic field would result in a non-zero y-intercept on the graph.	• The y-intercept on the graph represents the magnetic field present when there is no current, and a non-zero B value at emf = 0 is the magnetic field due to Earth.
• Some students did not understand that the presence of an additional magnetic field should have no effect on the slope of the line, and therefore the calculated resistance.	• Since the resistance of the solenoid was calculated using the slope of the best fit line, its value shouldn't be affected by the external field.
• Many students discussed Lenz's Law in terms of currents as opposed to magnetic fluxes. They also did not understand the concept of opposing	• The decreasing current resulted in a decreasing magnetic flux. The decreasing flux resulted in an induced current that generated a magnetic field that opposed the change.

changes in flux, rather than opposing flux.	
• Some students discussed Lenz's Law as the reason for the reduction of the current in the solenoid rather than the current induced in the loop.	• The decreasing current in the solenoid resulted in a decreasing magnetic flux. This change in flux induced a current in the loop to generate a magnetic field in the original direction of the flux.
• Many students used the radius of the loop rather than the radius of the solenoid when substituting into the area in Faraday's Law.	• The area used for the magnetic flux is that of the solenoid, not the loop.
• Many students used the resistance of the solenoid rather than the resistance of the loop when using Ohm's Law.	• The induced current is calculated by dividing the emf found from Faraday's Law by the resistance of the loop.
• Some students tried using the equations for an inductor to solve the problem.	• Stating emf is the derivative of magnetic flux with respect to time.

What resources would you recommend to teachers to better prepare their students for the content and skill(s) required on this question?

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