Chief Reader Report on Student Responses:

2018 AP® PHYSICS C: Electricity & Magnetism Free-Response Questions

- Number of Students Scored 25,074
- Number of Readers 380 (for all Physics exams)
- Score Distribution

Exam Score	N	%At
5	9,382	37.4
4	5,648	22.5
3	3,381	13.5
2	4,080	16.3
1	2,583	10.3

- Global Mean 3.60

The following comments on the 2018 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: Graph Sketch** | **Topic: Gauss's law and electric potential**

Max. Points: 15 | **Mean Score:** 5.10

What were the responses to this question expected to demonstrate?

- How to apply Gauss's law for different spherically symmetric distributions of charge.
- An understanding of the magnitude of electric fields at various locations for a given charge distribution.
- The ability to plot the electric field as a function of position and rank the electric potential as a function of position.

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

- Students frequently applied Gauss's law incorrectly.
- Course content includes how to apply Gauss's law, when it is applicable (high symmetry situations), and how to physically interpret each piece of the equation. Students struggled with each part of this.
- Electric fields and electric potential is typical course content and was covered well by this question.
- By using integration, as well as justify and graph sketching, the responses integrated student skills.

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 did not know to correctly integrate, but often attempted to apply Gauss's Law. When attempting to apply a change of variables dV = Adr, the students often use $4/3\pi r^3$ instead of $4\pi r^2$ for A.	Ability to integrate variable charge density over a volume (sphere)
Most errors occurred when students integrated with limits a to b when they should have integrated from 0 to a since outside of the sphere is a vacuum.	Ability to establish the correct limits of integration for a region outside a charged non-conduction sphere. This question was good at separating students who could integrate variable charge density to get charge and those who could not.
Most errors came from an incorrect area. Many students used $4\pi r$, $2\pi r^2$, $4/3\pi r^3$ instead of $4\pi r^2$. Also, many students never substituted the charge from ai and left the charge as simply q.	Application of Gauss's Law for region within a charged non-conductive sphere.

Many students started with electric field for a point charge ($E=kq/r^2$) rather than using Gauss.	
Many student never substituted the charge from aii; they simply left the charge as q.	Application of Gauss's Law for a region outside a charged sphere. This question was good at separating those who understood how to use Gauss's Law and those who don't.
Most errors occur from insufficient justification. Students failed to link the electric field/flux in the shell to the charge contained by the gaussian surface. Many students refered to the field outside the shell, not inside the shell.	Ability to determine and justify the induced charge on the inner surface of the conductive spherical shell.
Most students thought the shell would be polarized, when in fact the outer surface would have no charge since the field outside the shell was zero (as stated in the problem).	Ability to determine the induced charge on the outer surface of the conductive spherical shell. When students wrote E=0, it was hard to distinguish if they meant within the shell or outside the shell. Since the problem stated that E=0 outside of the shell, if the student did not specifically say "within the shell," they did not earn credit.
Many students graphed from 0 to a as if the sphere was conductive (zero field) or uniform charge density (linear), when it should be an r^2 function. Many students graphed from a to b and had the graph approach 0 at b when it should approach a non-zero value at b. It was difficult to distinguish if the student truly understood the shape of the electric field for the section $r=0\rightarrow a$. If the student made a mistake earlier in the problem and found the field to be linear and later graphed a linear function, they might be graphing a linear shape simply because it was a non-conductor, not for the function they derived.	Ability to sketch a graph of the electric field from zero to the outside edge of the shell.
Many students identified a changing potential with in the conductive shell.	Ability to rank electrical potential from the charge in the system at four different radii.

Many students identified the non-conductive sphere with a zero potential.	

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

- Teachers should devote class time to help students know how to integrate non-uniform charge distributions.
- Teachers should encourage students to study the difference between what happens to electric fields and electric potential inside of a conductor.

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

- The AP Central website has a module on electrostatics https://apcentral.collegeboard.org/pdf/physics-special-focus-electrostatics.pdf?course=ap-physics-c-electricity-and-magnetism that would be useful for teachers. It includes ideas on teaching electrostatics and Gauss's Law appropriate for AP Physics C.

- AP Physics C teachers can find useful resources on the Course Audit webpage and the AP Central Home Page for AP Physics C. The downloadable AP 1 and AP 2 lab manual may be useful for the teachers of the AP Physics C course, as well.

- 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: Graph data and calculate** **Topic: RC Circuits**

Max. Points: 15 **Mean Score:** 7.99

What were the responses to this question expected to demonstrate?

- The ability to use the given capacitance equation to create a linear graph from which the dielectric constant could be determined.
- The ability to identify the appropriate horizontal and vertical axis terms, record the necessary numerical calculations in a provided table, scale the axes appropriately, and plot the numbers accurately on the graph.
- The ability to label the axes, including units, and draw a best-fit line to describe their data.
- The ability to use the slope of the line to calculate an experimental value for the dielectric constant.
- The ability to apply Ohm's law and to combine resistors in series and in parallel to determine the current flowing from a battery when the capacitor is initially connected to a network of three resistors.
- Calculate the time constant of the *RC* circuit by using an expression that is not included on the provided equation sheet.
- Students were asked two questions about the experimental issues that might have led to the measurement of an unexpectedly long time constant.
  - The ability to identify intrinsic resistance of the wires or battery.
  - The ability to identify measurement error regarding the capacitor plate area, plate separation, or dielectric constant, as possible explanations for the unexpectedly long time constant.

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

The first part of the question is primarily an assessment of the student's ability to determine the independent and dependent variables that could be used to create a graph with a useful slope. It assesses their skill in carefully plotting the data, drawing a best-fit line, calculating the slope from the line itself (and not nearby data points that are not on the line), and dividing by constants to extract the dielectric constant from the value of the slope. Students should recognize the correct equation from the reference sheet, identifying κ as the symbol for the dielectric constant, and recalling the correct units for the various quantities. The majority of these points assess graphing skills.

In the second part of the question, the responses indicated that the students could describe the behavior of resistors in series and in parallel, recognize that an uncharged capacitor will have no potential difference across it and will initially act as a zero-resistance wire, and correctly apply Ohm's law to predict the current in the circuit. The responses also indicated that students could define and describe the "time constant" of an *RC* circuit and recall the expression $\tau = RC$, which is not given on the provided reference sheet. Finally, student responses indicated that the following experimental factors (intrinsic resistance, measurement uncertainty, etc.) could lead to higher than expected values for the resistance and capacitance.

In summary, the first part of the question does a good job using graphing skills to assess students' understanding of *RC* circuits, and the second part does a good job of using a schematic diagram to assess the students' understanding of *RC* circuits and sources of experimental error.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
Students were unsuccessful when interpreting an algebraic expression for the capacitance in terms of $y = mx + b$, and selected inappropriate variables to graph.	Students selected C vs. $1/d$, with or without the constants $A\varepsilon_0$, as the relevant variables to extract κ from the slope of the graph.
Students did not recognize which variables are changing and which are constants.	Students ignored the distractors (such as the number of sheets of paper in between the capacitor plates) and plotted the relevant dependent and independent variables.
Students chose to graph C vs d, which does not yield a line. After graphing this, they chose to fit a line to an obviously curved plot.	Students only graphed values that yielded a straight line, such as C vs 1/d. A few students erased and redrew their graphs when they realized they were not linear.
Students inappropriately chose data points instead of the best-fit line to calculate slope, and/or get the slope expression upside down, misread the axis scale, etc.	Students used points on their best-fit lines, carefully read the axes scales to find the relevant values, and showed all their work when calculating the slope.
Students did not show their work for simple calculations, and some did not write in the provided space. This was a common issue with the calculation of the equivalent resistance of the circuit.	Students wrote out the equivalent resistance of the parallel pair and added it to the series resistor to report the total equivalent resistance (120 Ω) of the circuit.
Students did not write a symbolic expression, show their numerical substitutions, or report a final answer with correct units.	Students wrote a symbolic expression, showed their numerical substitutions, and reported a final answer with the correct units.
Students used the theoretical relationship $\tau = RC$ to indicate that the resistance (or capacitance) must be higher than expected, but stopped short of giving an experimental reason, as requested by the question.	Students carefully read the question and gave a plausible experimental reason (internal resistance of the battery, capacitor plate separation too small, etc.) for the higher values of R and C they had indicated in the adjacent check boxes.

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

- Teachers should devote at least some classroom time to review common student errors on standardized exams.
- Teachers should encourage students to show their work, read the questions carefully, and check to see if the units are correct.

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

- The AP Central website has a module on electrostatics https://apcentral.collegeboard.org/pdf/physics-special-focus-electrostatics.pdf?course=ap-physics-c-electricity-and-magnetism that would be useful for teachers. It includes ideas on teaching electrostatics and Gauss's Law appropriate for AP Physics C.
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Question #3	Task: **Calculate with Calculus**	Topic: **Magnetic fields due to current; Electromagnetic induction**
	Max. Points: 15	**Mean Score:** 5.21

What were the responses to this question expected to demonstrate?

- The ability to apply Ampere's law.
- An understanding of the superposition of magnetic fields.
- An understanding of magnetic forces and their effects on current-carrying wires placed in a non-uniform magnetic field.
- The ability to apply Faraday's law.
- The ability to apply Lenz's law.

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

- Student responses indicated that it was difficult to capture the physical situation presented on the diagram given its 3D nature.
- Students had difficulty incorporating the two different perspectives presented.
- Students had difficulty interpreting which direction is to be considered as horizontal.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
The assumption that when two vectors are perpendicular to each other, the angle of their vector sum with one of the vectors is 45°, regardless of their magnitudes.	Correctly using a trigonometric function to find the angle. For example, $\tan^{-1}(1/2) = 26.6^0$.
Not using parentheses when squaring expressions.	Correctly writing algebraic expressions, for example $(B_1)^2 + (B_2)^2$.
Using "magnetic force" in place of "magnetic field."	Use of correct physics vocabulary, for example $B_2 = 2B_1$, instead of $F_2 = 2F_1$.
Answering a question in an area not designated for that question; e.g. giving an answer for part (b) under part (c).	Answering part (b) in the area designated for that question.
Using algebraic sum when calculating the magnitude of the sum of two vectors.	Understanding vector addition, for example $B = ((B_1)^2 + (B_2)^2)^{1/2}$.
Using the word "plane" in place of "direction."	Use of correct and precise vocabulary, e.g. saying "the two vectors are in the same plane"

	when actually meaning they point along the same line.
Overuse of the word “induced.”	Understanding Lenz’s law and using precise language in its reference, e.g. “the induced magnetic field points into the page and is decreasing within the loop, therefore a magnetic field is going to be induced in the same direction.”
Putting an equal sign between nonequal expressions in the course of derivation instead of writing expressions on separate lines.	Expressing algebra correctly. For example: Emf = (dϕ /dt)/R = I should be Emf = (dϕ /dt) (dϕ /dt)/R = I
Discerning between physical quantities and their derivatives when describing changes.	Using correct language in relation to calculus; for example, saying dØ/dt is increasing in place of the flux Ø is increasing.
Saying “the wire is pushed to the right and therefore it will rotate clockwise” without referring to the location of the applied force	Using correct language in relation to rotation , e.g. “the top part of the wire is pushed to the right and therefore it will rotate clockwise.”
Using the wrong argument: ”The magnetic field points into the loop and therefore the loop will induce a magnetic field in the opposite direction.”	Correct application of Lenz’s law; understanding it relates to changing magnetic flux (the induced field opposes the change in magnetic flux, not the direction of the magnetic field by itself).
Forgeting about Faraday’s law and/or relating Faraday’s law with Ohm’s Law to find an electric current.	Knowledge of and combining different physical principles in a process of derivation of a physical quantity. Once the emf is found, students should continue on, using Ohm’s law to find the current.

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

- Teachers should provide classroom time for a review of vector algebra. Many students on the exam knew the physics, but made errors adding vectors.
- Teachers should ensure that students have plenty of practice applying Lenz's law to determine the direction of induced currents.

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

- The AP Central website has a module on electrostatics https://apcentral.collegeboard.org/pdf/physics-special-focus-electrostatics.pdf?course=ap-physics-c-electricity-and-magnetism that would be useful for teachers. It includes ideas on teaching electrostatics and Gauss's Law appropriate for AP Physics C.

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