Chief Reader Report on Student Responses:

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

Set 2

- 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:** Analyze a circuit **Topic:** RC circuits

Max. Points: 15 **Mean Score:** 7.36

What were the responses to this question expected to demonstrate?

- How a capacitor acts in a circuit
  - Current doesn't flow through a completely charged capacitor. In steady-state, the current through the capacitor branch is zero.
  - Where current does flow, V=IR
  - Charge on a capacitor is related to the voltage across it
  - Energy can be stored in a capacitor

- How a capacitor discharges:
  - Current and charge are time dependent during the discharge phase and can be related by a Kirchhoff's loop rule that contains q and dq/dt.
  - The charge on a capacitor decreases exponentially.
  - The current decreases as the charge on the capacitor decreases.
  - The initial current depends on the potential difference across the capacitor and the resistance of the loop
  - An open switch means current can't flow.

- Energy conservation
  - Energy in a capacitor can be dissipated in a loop containing resistance.
  - All energy will eventually be dissipated
  - No energy can be added to a single loop

- Exponential decrease of current
  - Curve starts at an initial value (no vertical asymptote).
  - Curve has a zero horizontal asymptote.
  - Rate of decay (slope) decreases

- Use of a correct original equation to derive a specific result using given symbols
- Recognizing when current can and cannot flow
- Graphing exponential decay with proper start and asymptotes
- Recognizing energy flow in various forms

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 students were able to determine what happens to a circuit when a capacitor is introduced with various success:
  - Many students recognized that when the capacitor is fully charged, current doesn't flow in that branch.
  - Fewer were clear on how the above fact changes the equivalent resistance of the circuit.
  - Few students recognized that a Kirchoff loop rule could lead to a solvable differential equation. Many of these were wrong only by a negative sign, so the students didn't recognize the subtle point of current as an actual representation of decreasing charge on the capacitor.

- Students were able to demonstrate understanding of the storage of energy by a capacitor and how it is dissipated, including a graphical representation of decreasing current, starting from a specific value and decaying to zero over an infinite length of time.
  - Students could mostly draw an exponentially decaying curve that has a particular starting value.

- The open switch in the circuit, cutting off the capacitor from the original power source, was well understood, though there was still confusion about whether the cut off resistors still contribute to the equivalent resistance of the circuit.

- Students understood that the energy stored in the capacitor would be dissipated by the resistors, and many made some subtle points about other sources of energy loss, such as in the wires. A small percentage of the students clearly misunderstood the question.

- Very few responses showed a logical progression from an original equation to a final answer. Many showed no original equation containing general variables.

- Students were able to use Kirchhoff's loop rule, but it was often applied incorrectly. They often didn't recognize that current wasn't flowing in a particular branch and tried to include that loop in the equations.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Resistors in loops where current isn't flowing were used to calculate equivalent resistance in a circuit.	• When current isn't flowing in a parallel branch, the resistors could be added in series – no special parallel combinations are needed.
• A capacitor always ends up with the same potential difference as the battery used to charge it – this was the most common misconception. More than 70% of students wrote that $V_c = V_o$.	• The correct method to calculate the potential difference across the capacitor is to realize that when no current flows, the capacitor is in parallel with the R resistor, so that its potential is the same as the potential across the resistor.
• Once the switch is opened, the current now refers to the current from the capacitor with the two resistors in the right-hand circuit. Many students thought that the initial current when the switch is initially opened is the same as the current calculated from the steady state situation in part (a). Since that answer was $V_o/3R$, it was difficult to tell if students understood this point at all – the 3R in the first circuit that is the same as the 3R in the second, and probably led to some student confusion.	• A correct answer for the initial current would include a recognition that the new circuit starts with a voltage from the capacitor that was the result of charging when the switch was closed. It would also include a total resistance of 3R for the open-switch circuit. Since most students thought that the capacitor would be charged to the battery voltage, in many cases it was impossible to tell if they were using the initial battery current or the final open-switch current.
• The graph of the decay goes to zero at 3RC or 5RC	• An asymptote should be indicated by an arrow near the end of the curve, showing that the value of the quantity, in this case

	current, decreases to zero over an infinitely long time.
• Steady-state solutions can still have a time dependence. Many students had memorized the time-dependent form of current or charge and wrote that for the steady-state solution.	• In the steady state, the current has a constant value, and so does the charge.
• In general, students did not recognize the difference between a constant and a variable. This is not exactly a misconception, but a common mistake: the answer was not given in terms of the given constants. Many answers contained I or Q, even though values for those quantities should have been substituted or calculated.	• The answers should be expressed in terms of given quantities, in this case V_o, R and C.
• The current for the discharge was usually given as dq/dt rather than –dq/dt.	• For a capacitor discharge, the current is the opposite of the normal dq/dt because q represents the charge on the capacitor. So $I = -dq/dt$.

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?

- Teachers should emphasize that a capacitor does not always acquire the voltage of the battery. A careful treatment of potential difference should be made. Try to use some example problems where a capacitor is in series with a resistor, and the combination is put across another resistor. In other words, it's important to treat some more complex circuits that are combinations of series and parallel elements.

- The time-dependence of the circuit should be taught in terms of the loop equation. It would be nice for students to be able to decide what the discharge graph looks like just by thinking about what will happen when a switch opens. Try to make the point that electric potential drives a circuit, both for charging and discharging, for capacitors and inductors. Then students do not have to memorize equations. They can get the form of the equation by thinking about the potential differences and the way that charge will flow.

- It can be difficult to enforce, but every calculation and derivation should start with an original equation that contains only variables and physical constants. In addition, answers should be written in the form of an equation with two sides. Just writing an expression in the middle of the page shows undeveloped thought processes and it is impossible for the reader to tell where the expression came from and whether it represents the needed quantity.

- Often doing a demo/lab activity/lab of the basic scenarios that you could anticipate on your own exams or the AP exam gives students a memory reference to work or build off of. It is often obvious in student responses when students have built or been shown a similar lab activity.

- Review with students the difference between "Derive," "Calculate," and "Determine." Many students lost points for not completing a derivation as they were not starting from a basic equation and developing from there.

- Direct students to write briefly; don't write a paragraph or two when a sentence will do.

- Check boxes are generally not worth any points unless accompanied by a justification, so have students always justify a choice they make. TIPERS is a good resource for giving students practice on this.

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:** Non-hollow conducting sphere **Topic:** Gauss's Law

Max. Points: 15 **Mean Score:** 6.27

What were the responses to this question expected to demonstrate?

- Understand and apply Gauss's Law to situations with variable charge density and unusual geometry
- Use calculus in determining the total charge of an object with variable charge density
- Interpret quantitative results and illustrate their functional behavior through sketching
- Understand and apply the concept of electric potential and electric potential difference
- Apply Newton's Laws and Conservation of Energy concepts to the behavior of electrostatic charge
- Calculate values of E & V and use appropriate units

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?

- Students had moderate success in recognizing the need for integral calculus to determine the total charge on the object to use as Q enclosed. However, of those who applied calculus, roughly half effectively set up and solved for the correct charge.

- Most students were successful in determining the area of an appropriate Gaussian surface to determine the electric field at the outer surface of the sphere. Some students did not start with an appropriate statement of Gauss's Law (as provided on the equation sheet). Not starting with the full integral statement disallows the emphasis on symmetry; not stating the closed integral may show misunderstanding of the difference between simple flux through a surface and total flux through a surrounding surface.

- Sketching the electric field presented another challenge to the students in that the question did not lead them easily to a correct answer. Questions usually have students determine an electric field function before developing a sketch to illustrate the behavior. This question had students determine the value of the E-field at the surface.
    - In order to sketch the function, students were required to look more closely at the functional behavior of the charge in the integrand to determine exactly how q varies in the region of variable charge. This is a difficult skill and one that few students were successful in using to identify the rising decay behavior that would lead to a correct response for the middle section of the sketch.
    - Students had fewer problems determining the E-field behavior in the inner and outer regions because these follow basic principles and understandings of Gauss's Law; zero E field if no charge is surrounded and point charge behavior when outside the charge.

- Students were also asked to tie together an understanding of the relationship between electric field and electric potential.
    - Many students seemed to only have a rudimentary understanding of the relationship between E and V, often quoting and misapplying equations from the equation reference sheet.
    - Many students would write that $\Delta V = -$ integral of Edr, but would stop there or simply insert the numerical answer from an earlier section, which demonstrates their fundamental misunderstanding of this relationship.

- Some students would also write $V = Er$, demonstrating a failure to understand the need to integrate when the E field varies with distance (which they had just graphed) or not recognizing that the E field was indeed varying with distance.

- Students were able to recognize and correctly apply Newton's 2nd law to determine the acceleration. There was some confusion about which charge to use in the acceleration equation. This was exacerbated somewhat by the unfortunate confluence of the pre-multiplier "1.6" in both part (a) and for the q substitution for part (ei).

- Some students were able to apply conservation laws to the situation. Many did not respond correctly in either stating or applying potential *difference* to determine the final velocity of the proton. This again supports the idea that there is a fundamental misunderstanding of how electric potential plays a role in electricity.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• $Q = \rho V$ is valid even with a variable charge density.	• Variable charge density must be integrated as a function of radius in order to find total charge.
• Q = the integral of $\rho\, dV$ is the same as the integral of $\rho\, V dr$ or similarly: Q = the integral of $\rho\, dr$.	• A proper integral to find total charge Q based on a volume charge density is the integral $\rho\, 4\pi r^2\, dr$ for a sphere.
• Using $A = 2\pi r$ or $A = \pi r^2$ to represent the Gaussian surface of a sphere	• Spherical Gaussian surfaces should have an area of $4\pi r^2$.
• The units for electric field are N/m or C/m or V.	• Proper and common units for electric field are N/C or V/m.

• The electric field in a region where no charge is enclosed has a constant or varying non-zero-value.	• For a region where no charge is enclosed, the value of the electric field is zero.
• Applying V = –Er to determine the voltage at a given radius based on the E field at that location	• ΔV = –Er is only valid in constant E field regions. Regions of variable E field should be determined using ΔV = – integral of E dr.
• Substituting a numerical value for E in the integral or linear expression for ΔV	• ΔV= –integral Edr is used when the field is a function of position.
• Making a statement of energy conservation without noting change in energy: U = K	• A valid energy conservation statement should include both initial and final conditions; any terms that go to zero should be explicitly stated.
• Not starting with the full integral form for Gauss's Law	• Starting with the form as given on the equation page

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?

- In a "calculate" question, students should show explicit substitutions. While solving problems in class, teachers should model how to effectively show their work.

- Practice drawing E field and electric potential graphs as a function of radius. Draw identical shapes for conductors vs. non-conductors and highlight the similarities and differences between them. Be deliberate with finite values, concavity and asymptotes. Remind students that an asymptote should never be shown to touch the line it is approaching.

- Review situations in spherical, cylindrical and planar non-conducting geometries, with and without varying charge densities, and note when integration is required to determine total charge and when it is appropriate to simply multiply ρV. Review the appropriate expressions for dV in each of the situations.

- Once magnetism has also been completed, work through examples to compare and contrast Gauss's Law and Ampere's Law. Illustrating the difference between a surface integral and a line integral can promote better understanding of these key physics concepts.

- When solving conservation of energy equations in class, always show "zero" terms being eliminated rather than assumed.

- Review the AP Equation sheet in advance of the exam, including the calculus and geometry sections, so students are aware of the equations and constants available to them. Similarly, be sure to highlight equations that have names, such as Gauss's Law, so students are familiar with what is being asked of them when a problem uses this vocabulary.

- Working with units, especially on a final answer, should be emphasized consistently in class.

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.

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Question #3

Task: Analyze motion of a charged particle in a magnetic field

Topic: Experimental – Magnetic Forces

Max. Points: 15

Mean Score: 5.72

What were the responses to this question expected to demonstrate?

- Identify the magnitude and direction of forces on charged particles in both electric and magnetic fields
- Recognize that charged particles will move in circular motion when under the influence of magnetic forces
- Derive expressions utilizing concepts of Newton's Laws and Energy Conservation
- Linearize data in order to extract physical quantities from experimental data
- Construct an appropriate graph using experimental data
- Utilize math skills, such creating a best-fit model and calculating a slope to extract desired quantities

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 majority of students were successful in recognizing the direction that a charged particle will be deflected and the path it will take.
    - The challenging aspect of the first question was to recognize that the particle was negatively charged, which reverses the force determined by the right-hand rule.
    - Many students perhaps did not fully understand the intent of the question since they would often describe curved paths that were general but not saying "circular" or "semi-circular".
    - A few students noticed the nearby presence of a positively charged plate would cause the sphere to deviate from the path it would take if it were affected by only a magnetic field. It would have been better to explicitly state that $E = 0$ to the right of the plates.

- Students were to derive an expression for velocity based on energy principles, but some did not begin with a fundamental relationship relating potential energy to kinetic energy.
    - The student's understanding of the connection between the difference in electric potential and the change in potential energy was sometimes unclear. This was because the problem statement unfortunately defined V as the potential difference, so the question did not assess how well students understood the difference between the two physical quantities.
    - The two derivations also tested the ability of students to recognize when to substitute appropriate quantities and when to algebraically combine terms into a compact statement. Students were moderately successful in this, although many did not recognize when to mathematically simplify expressions.
    - Many students recognized the need to start with a statement of centripetal force equated to magnetic force, but some did not follow through with the velocity substitution nor a simplification of the expression if they did.

- The second part of the question probed the students' ability to linearize and plot experimental data, asking the students to identify appropriate quantities to be plotted based on their derivation in the previous section.
    - Some students did not recognize that they were only to use the V and B data and instead created *new* data for either velocity or acceleration *calculated* from the given data. This required the numerical use of the m/e ratio, which was the very experimental ratio the data was to ultimately supply.

- Some students also used various combinations of quantities in their plots that could yield the correct answer, but made it more difficult to plot (and ultimately get correct). For example, some would plot $(Br)^2$ vs V.
- Many incorrect responses to this part did expose a fundamental misunderstanding of data linearization. Perhaps half of the students simply plotted V vs B and assumed the slope was the desired ratio, seemingly not connecting their work from different sections.

- Most students were able to properly create the appropriate graph, however attention to detail was often lacking.
  - Some students would forget certain axis labels or fail to recognize that the units must match the quantity plotted. For example, plotting B^2 required the units to be $(T \text{ x } 10^{-3})^2$, etc.
  - Another challenge was to scale the graph to present the data in such a way that the analysis is more accurate. Many students plotted one or both sets of data with scaling (from 0) that caused the data to be too compact while some used quantitative breaks in the axes. Most students were able to plot data correctly based on the chosen scale.
  - Best-fit models were often successful, but in many cases, lines were unsuccessfully drawn free-hand, in ink, with multiple attempts, or with an unbalanced number of points to either side of the line.

- In order to extract the final m/e ratio, a demonstration of mathematical skills, such as properly determining slopes from the modeled line, using that slope in the final calculation, etc., were assessed.
  - The most common errors were in the slope calculation, including neglecting the order of magnitude of the axis values and misapplying the diameter of the electron path as the radius in the calculation.
  - Students were not very successful at relating the slope of their graph to the m/e ratio. In the majority of responses there was no work after an attempt to calculate the slope of the line.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• (a) The sphere is deflected by the magnetic force according to the right-hand rule.	• Because the sphere is negatively charged, it is deflected in the direction opposite to that given by the right-hand rule.
• (b) The speed of the sphere can be determined from the magnetic force and Newton's 2nd law.	• The electric force is responsible for accelerating the sphere. Energy principles are the most direct path for finding the speed of the sphere in terms of the potential difference.
• (d) The slope of a B vs. V graph can be related somehow to the mass-to-charge ratio.	• The expression determined in part (c) for the radius of the path taken by the sphere (and that taken by the electron in the second scenario) should be carefully examined and manipulated to determine a linear relationship whose slope could be used to determine the m/e ratio.

• (d) Velocity or acceleration data calculated and used in linearization	• Only data given (to some power) is used for linearization and to determine the *m/e* ratio.
• (e) The choice of scales for the axes is unimportant for determining the result.	• Choosing a scale that allows the data points to span at least half the graph area greatly increases the student's ability to accurately determine the slope of the graph, and hence the *m/e* ratio.
• (e) The choice of increment in the scaling is awkward so points are mis-plotted	• The increment to choose in scaling the axes should be natural (1,2,5,10, etc.) so that it allows for easy and accurate plotting between major increments
• (f) The slope of the graph is the desired answer.	• The specific relationship between the graphed quantities and the desired *m*/e ratio must be understood so that the numerical value of the slope can be converted into a numerical value of the *m/e* ratio.

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?

- Review the differences in the meaning of verbs used in prompts. “Derive,” “Calculate,” and “Determine” all have different meanings on AP exams. Derivations are the most strict and require students to start from a statement of fundamental physics or laws (such as those on the equation sheet) and methodically substitute and algebraically manipulate as appropriate to determine a final expression.

- Practice doing derivations with students so that they understand the general procedure for various types. Remind students that they should always check that their final expressions only use allowed variables.

- Emphasize the importance of checking the sign of the charged particle when applying right-hand rules.

- Emphasize that when writing conservation laws, all appropriate terms should appear on both sides of the equation and those that are zero should be explicitly stated.

- Emphasize the importance of reading the question carefully and answer what it asks for. In part (d) the prompt asked for quantities to be plotted, not units.

- Practice the linearization of experimental data, from using expressions that describing phenomena to plotting and analyzing data. The slope does *not* necessarily need to equal the quantity that is to be determined. Emphasize that only one variable should be on each axis and the units must match.

- Emphasize the importance of calculating slopes of best fit lines from the line and not using data points. Calculations need to be explicit, fully showing both points used.

- Practice relating the slope to the desired physical quantity.

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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