Chief Reader Report on Student Responses:

2022 AP® Physics C: Electricity & Magnetism Set 2 Free-Response Questions

• Number of Students Scored	19,978		
• Number of Readers	471 (for all Physics exams)		
• Score Distribution	Exam Score	N	%At
	5	6,301	31.5
	4	4,717	23.6
	3	2,855	14.3
	2	3,608	18.1
	1	2,497	12.5
• Global Mean	3.44		

The following comments on the 2022 free-response questions for AP® Physics C: Electricity & Magnetism were written by the Chief Reader, Brian Utter, University of California, Merced. 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: Short Answer
Topic: Electrostatics
Max Score: 15
Mean Score: 5.70

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Determine the induced charge on the surface of a conductor in the presence of other cylindrical charge distributions.
- Use symbolic and numerical reasoning to derive and calculate electric field strength and electric potential difference using Gauss's law and the definition of electric potential.
- Calculate the potential difference between two points by integrating the electric field over a distance.
- Sketch graphs showing the relationships between electric field and electric potential with respect to radial position for static cylindrical charge distributions.

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?

- Student responses were strongest in using the symbolic derivations of electric field strength using Gauss's law and the potential difference between two points due to an electric field.
- Derivations typically start with relationships taken directly from the equations sheet. However, to earn credit, the student must use the equation in context. Many lower-scoring responses simply listed the starting equation without showing additional work.
- Because this specific problem required students to use cylindrical symmetry, as opposed to the more commonly used spherical symmetry, many responses simply showed the canonical spherical derivation. Those responses earned little if any credit.
- Correctly identifying the enclosed charge within the volume of a Gaussian surface is of critical importance in this problem. Many students struggled to discriminate between enclosed charge and charge outside of the Gaussian surface.
- Student responses were weakest in showing carefully sketched accurate graphs representing the same relationships that were derived symbolically.
- Functional dependence that is not linear should be drawn with care to ensure behavior near domain boundaries is consistent (e.g., a decreasing function should keep decreasing and not show a small increase at the end of the domain).
- Linear dependence should be drawn with a straight edge. All students are allowed to use a ruler for exactly this purpose, and they should use it for drawing straight lines in graphs. Concave free-hand lines may not earn credit for a straight-line segment when other scored segments are either concave up or concave down. Ruled versus unruled lines are extremely easy to distinguish.
- Vertical dashed lines provided as part of the graph prompt are meant as segment boundaries and are not intended to show vertical asymptotes. Many responses clearly reflected student belief that these lines must be vertical asymptotes on the graph. Showing continuity of the graphed segments at these domain boundaries was a critical scoring feature. Responses that were rushed or where some care was not taken at the boundaries showed discontinuities and resulted in the loss of response credit that would have otherwise been awarded.

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 electric potential function must be continuous through the spatial domain, while the electric field function can be discontinuous. Many students failed to discriminate between these two different behaviors.	• Continuous lines or curves that were fit together in piece-wise fashion were produced for potential versus position graphs. Electric field graphs that had jump discontinuities had corresponding cusps in the electric potential graph at that position.
• Many responses suggested students did not know the difference between a constant R and the variable r and indiscriminately used them interchangeably when performing integrations of the electric field function to derive an electric potential function.	• Responses showing good discrimination between the constant (symbolic quantity) R and the variable r replaced the R with r when rewriting the electric field function in order to integrate the function with respect to dr.

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?

- Using a ruler for straight line graphs is a must for ensuring students earn credit for these segments. Students must use rulers for creating these graphs on the AP physics tests. Have rulers available and encourage their use every time an assessment is given in class. Remind students that straight line segments drawn free hand will not receive credit. Stick to this for in-class grading.
  - Discuss with the AP coordinator the necessity of having sufficient rulers so that all students will receive a ruler when materials are distributed for the AP physics exams. Having this conversation in the fall makes it more likely that any supplies needing to be ordered will have arrived by the May testing window.
- Students should have experience applying Gauss's law and the definition of potential difference in more than spherically symmetric contexts. Both planar and cylindrical examples should be used to fully develop the utility of the methods.
  - Equations for surface area and volume for a cylinder are provided in the equations sheet. Students should practice using the Equations and Constants pages so that the students are familiar with the locations of the various types of equations available prior to the exam administration.

Question 2

Task: Experimental Design
Topic: RC Circuits
Max Score: 15
Mean Score: 7.35

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Identify the behavior of capacitors in circuits, specifically the properties of charging and discharging RC circuits, including their time dependence.
- Draw a circuit diagram that allows a capacitor to be charged and then discharged through a resistor and ammeter using given circuit elements.
- Use Kirchoff's and Ohm's laws to write a differential equation for a discharging RC circuit that can be integrated to determine the current through the capacitor circuit as a function of time.
- Associate the parameters in an equation for an RC circuit with the characteristics of a corresponding graph.
- Use a graph to determine the internal resistance of a capacitor using the slope of the line and an equation for the current in a circuit with a discharging capacitor.
- Provide reasoning to justify a claim concerning the changes of the slope and intercept of the graph.

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 majority of students were not able to construct a circuit diagram that could successfully charge and discharge a capacitor. Many students drew a diagram that looked similar to diagrams found in textbooks but with major errors, such as short-circuits or incorrectly placed switches. A very common incorrect circuit was comprised of every component connected in series.
- The majority of students were able to apply Kirchhoff's loop rule to the capacitor and resistor and also substitute relevant terms. A minority of students were able to then develop a differential equation. Few students continued their work toward a successful solution to the differential equation.
- Most students were able to draw the best-fit line; few students drew curves or erratic lines. Those students who used a ruler to draw a straight line were much more able to draw an accurate best-fit line.
- The majority of students were able to calculate the slope of the best-fit line. About half of the students correctly determined that the slope of the best-fit line is equal to capacitance and were able to determine the internal resistance of the capacitor. A small number of students used a system of equations to successfully determine the internal resistance. It appeared that those students who wrote an expression like " $y = mx + b$ " on their exam and then attempted to apply a physical meaning to each term in the equation did very well.
- Many students correctly interpreted the phrase "The ammeter is found to be nonideal" to mean that the ammeter has internal resistance, but many students thought that the phrase also meant that there was now an additional resistor or source of resistance, which would change the shape of the graph.
- Those students who had earlier deduced, in part (c)(ii), that the slope of the best-fit line is equal to capacitance were able to correctly state that capacitance is independent of resistance. Many students, when attempting to provide mathematical reasoning, described the relationship between the time constant and the resistance of the variable resistor to be directly proportional rather than linear.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Ammeters can be connected in parallel to circuit components to make accurate measurements of current.	• Ammeters were connected in series with circuit components.
• Assuming that the intercept, slope, or area of the graph is internal resistance or capacitance without analysis.	• Students who used "$y = mx + b$" to determine the physical significance of the graph's intercept, slope, or area bound between the curve and the horizontal axis had great success.
• That capacitors in the circuit drawn by the student can be charged/discharged spontaneously without a switch.	• The flow of charge to a capacitor can be controlled, among other things, by a switch. Successful circuit designs used a switch for a purpose.
• Many students lacked the ability to mathematically assess the features of a graph.	• Understanding that changing a valid data range for the provided linear graph does not change the slope of the graph.

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?

- Encourage students to use a ruler to draw straight best-fit lines. AP physics is the only AP Exam that allows students to bring a ruler into the test room.
- Encourage students to compare the design and function of real circuits with circuit diagrams.
- Whenever students are using or drawing a graph, ask the students to deduce the physical significance (if any) of its intercepts, slope, and area bound between the curve and the horizontal axis. It takes little time and is very useful.
- Have the students create a graph for a system with a particular time constant and then design and build their own experiment.

Question 3

Task: Short Answer
Topic: Electromagnetism
Max Score: 15
Mean Score: 4.91

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Relate an increasing current in a solenoid to an induced current in a loop that is placed inside the solenoid.
- Determine the properties of a current induced by a changing magnetic field using Faraday's law and Lenz's law.
- Apply appropriate right-hand rules to determine directions of magnetic forces and fields.
- Relate the induced current to the energy dissipated within the loop.
- Identify what change could cause the induced current in the loop to be experimentally smaller than anticipated.
- Determine how the induced current would be different with a loop that had both a larger area and larger circumference.

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?

- Most students were able to correctly identify the direction of the induced current in the loop, but few students were able to successfully articulate the correct justification for their choice.
- Many students struggled with recognizing that the induced current was a result of a *changing* magnetic flux through the loop, not just because an external magnetic field or magnetic flux was present.
- Many students were able to successfully relate the current in the solenoid to the solenoid's magnetic field, but few students connected this concept to Faraday's law and Ohm's law to determine a correct expression for the induced current. Even fewer students recognized that the density of loops in the solenoid was 500 turns per 0.25 meters.
- Many students recognized that the energy dissipated through the loop for the first two seconds of the experiment depended on an expression for power, but few students successfully connected this concept to the resistance in the loop and the response for the induced current in the previous section.
- Many students recognized that because the magnetic field inside the solenoid is uniform, a plausible explanation for the fact that a current measured as less than expected was due to the plane of the loop not being perpendicular to the solenoid's axis. Students also, in large part, correctly justified the reasoning behind this result as due to the smaller amount of magnetic flux and induced electromotive force.
- Some students correctly identified that the current would be larger in a second loop with a radius twice as large as the first loop, but very few students successfully justified that it would be exactly twice as large due to the quadrupling of the induced electromotive force and doubling of the internal resistance.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Not understanding that induced currents are caused by *changes* in flux, not just flux.	• The current function for the solenoid produced an increasing magnetic flux through the loop's area, and because of Lenz's law, the induced current in the loop will oppose this change in flux.
• Not recognizing that a linearly increasing solenoid current and magnetic field through the loop would induce a constant current in the loop.	• High-scoring responses that addressed the preceding point recognized that the derivative of a magnetic field function that is linear would result in the induced electromotive force to be constant.
• Not recognizing that the induced current and resistance in the loop act like a normal circuit.	• The energy dissipated in the loop is due to the constant induced current (or emf) and resistance of the loop. The increased size of the loop would affect the amount of resistance in the wire as well as the magnitude of the change in flux that would induce the emf and current produced in the loop.

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?

- There is a big difference in what happens when there is constant magnetic flux as opposed to changing magnetic flux.
    - Be very intentional about phasing when students are talking about magnetic flux, change of magnetic flux, and induced potential differences with Faraday's law.
- Write justifications using complete sentences that incorporate specific physics terms and concepts.
    - Similar to the AP Exam, require students to write an explanation that actually makes sense as it is written, rather than what a student "was trying to say." Logical written statements should incorporate correct physics terminology and concepts while completely answering the question.