Chief Reader Report on Student Responses:

2024 AP® Physics C: Electricity and Magnetism Set 2

Free-Response Questions

• Number of Students Scored	27,967		
• Number of Readers	685 (for all Physics exams)		
• Score Distribution	Exam Score	N	%At
	5	9,856	35.2
	4	6,044	21.6
	3	4,127	14.8
	2	4,856	17.4
	1	3,084	11.0
• Global Mean	3.53		

The following comments on the 2024 free-response questions for AP® Physics C Electricity and 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: Electrical Potentials and Fields
Max Score: 15
Mean Score: 6.71

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Determine the absolute value of the electric flux due to a symmetrical charge distribution by using Gauss's law.
- Use an energy bar chart to qualitatively represent the absolute value of the work done by an external force when moving a test charge between equipotential lines.
- Calculate the magnitude of a component of an electric field by using electric potential values.
- Indicate the direction of the motion of a positive test charge after the test charge is released from rest in an electric field, requiring the application of both Coulomb's law and the relationship between electric field vectors and equipotential lines.
- Derive the relationship between electric potential and the location of a point that is located on an axis that is extended from the end of a rod of uniform negative linear charge density by using integral calculus.
- Sketch a graph representing the value of the electric field along an axis that is produced by a rod with a uniform negative charge density, resulting in a negative inverse square relationship between the field and the distance from the rod.

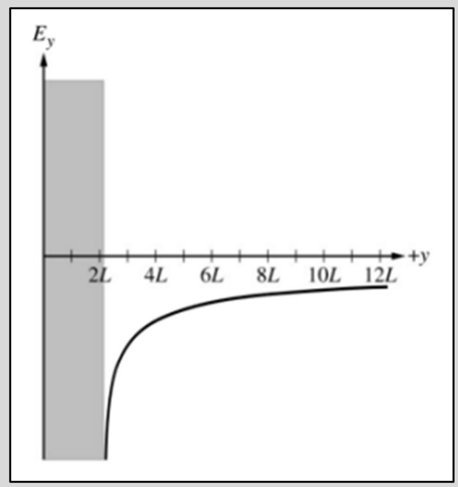
How well did the responses address the course content related to this question? How well did the responses integrate the skill(s) required on this question?

- Most responses were able to identify that Gauss's law was required to find the absolute value of the flux due to only the enclosed charge; however, some responses struggled with a unit conversion from nC to C when determining the flux value.
- Very few responses included appropriate units for flux and electric field calculations.
- Some responses did not distinguish between magnetic and electric flux or fields.
- Most responses acknowledged that no work was required to move a charged object along an equipotential line, and the responses marked the bar graph accordingly.
- Many responses recognized that moving a charge through half the electric potential difference would result in the work done by an external force changing in some way, but only some responses understood that it would take half the work.
- Many responses used the correct relationship between electric potential and electric field to approximate the field value at the given point; however, some responses used values of electric potential that were far from Position B, while other responses failed to account for the 0.4-unit scaling on the axis.
- Many responses incorrectly checked multiple check boxes when describing the motion of the test charge that is placed at Position C, indicating components instead of net force as directed.
- Nearly all responses addressed the Coulomb forces between the test charge and the electric field of the test charge and rod. However, few responses correctly considered that electric field vectors are always normal to equipotential lines. Many responses used a Newton's second law approach but failed to consider the relative magnitudes of the forces.

- Many responses correctly started the derivation for electric potential with the relationship $\Delta V = -\int \vec{E} \cdot d\vec{r}$, but failed to account for the changing electric field with respect to *y*, instead replacing E with $\frac{kq}{r^2}$. A large number of responses tried to build backward and "reverse engineer" the starting point of the derivation instead of beginning the derivation with a fundamental idea, using algebraic manipulation to rearrange the provided equation. A few responses tried to apply integral calculus to the finished equation instead of determining the equation by derivation. These methods did not show a clear understanding of the relationship between the electric potential and a point relative to the rod.
- For the graphing task, nearly all responses showed an inverse relationship between the electric field and the position along an axis that extends from the end of the rod, though many responses did not take into account direction, showing a positive curve instead of the appropriate negative curve.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Using the definition $\Phi_E = \oint \vec{E} \cdot d\vec{A}$ to determine electric flux is not the correct approach to this scenario because this method requires the surface area of the closed shape that is created by the equipotential line.	• For any closed, symmetrical charge distribution, Gauss's law allows that $\Phi_E = \oint \vec{E} \cdot d\vec{A} = \frac{q_{enc}}{\varepsilon_0}$, regardless of the surface. The enclosed charge should be in Coulombs, requiring a unit conversion from $1.0\ \text{nC}$ to $1.0 \times 10^{-9}\ \text{C}$. Thus, using Gauss's law: $$\Phi_E = \frac{q_{enc}}{\varepsilon_0} = \frac{1.0 x 10^{-9}\ \text{C}}{8.85 x 10^{-12} \frac{\text{C}^2}{\text{N} \cdot \text{m}^2}} = 113 \frac{\text{N} \cdot \text{m}^2}{\text{C}}$$
• It was common for responses to incorrectly use Newton's second law to determine the net Coulomb force that is exerted on a test charge because it was common not to consider the relative sizes of the vectors that must be analyzed. For example: o Claiming that forces from two different charged objects will offset without knowing the relative sizes and distances; o Ignoring the effect of one charged object because the charged object is "farther away" from another charged object or location; and o Not using the information provided by the equipotential lines.	• Begin with plotting the electric field vector using the information provided by the equipotential line. At all points, including Position C, the electric field is perpendicular to the equipotential lines, and the field vectors point from high potential to low potential. A positive test charge will move parallel to the field. Therefore, the test charge will move in the -*y* direction at Position C. • There is insufficient information to create a Newton's second law argument.

• It was common to derive the provided expression by starting with the final answer and working backward.	• Begin by considering the relationship between charge, distance, and electric potential difference, such that $$V = \frac{1}{4\pi\varepsilon_0}\sum\frac{q_i}{r_i} = k\int\frac{dq}{r}$$ where r is the distance $r = y_P - y$ and $dq = -\lambda\, dy$, because the total charge is linearly dependent on the length of the rod. In this case, $0 \le y \le 2L$, and the electric potential can be determined by $$V = -k\lambda\int_0^{2L}\frac{1}{y_P - y}dy = -k\lambda[-\ln\left(y_p - y\right)]_0^{2L}$$ This will simplify to the provided expression.
• It was common not to include the negative sign when graphing the electric field of the rod of uniform negative linear charge density.	

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

- Include practicing task models that require careful reading and processing of the scenario before answering questions that are associated with the scenario. A number of responses include errors that could be avoided with a more thorough reading and analysis of the prompt.
- When asked to calculate or derive, remind students to show all mathematical steps. By including more examples of the problem-solving process, it better allows students to demonstrate fully their understanding of a concept as opposed to simply providing a numerical answer.
- Practice deriving more complex formulas by using Newton's laws, conservation of energy concepts, and other concepts that are addressed in the reference booklet. Remind students to begin a derivation with the fundamental idea, rather than the final solution. Attempting to work backward will hinder future progress.
  - There is excellent, step-by-step derivation practice in the AP Physics 1 Workbook. While the mathematical requirements on the AP Physics 1 exam are less than what is typically assessed on an Electricity and Magnetism exam, it is good practice in developing the skills and the thought processes that eventually translate to calculus.
- Regularly require students to justify their answers by using appropriate content-specific vocabulary.

- Require students to annotate at least some of their mathematical calculations and derivations on homework and/or other formative assessment tasks. This will allow the teacher to provide feedback on student understanding and communication of ideas. Consider assigning grades for annotations instead of solutions.

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

- Teachers should direct students to the AP Daily videos on electric potential and electric fields.
- Teachers should assign topic questions as well as personal progress check items to monitor progress being made in the mastery of content.

Question 2

Task: Experimental Design
Topic: Circuits
Max Score: 15
Mean Score: 6.48

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

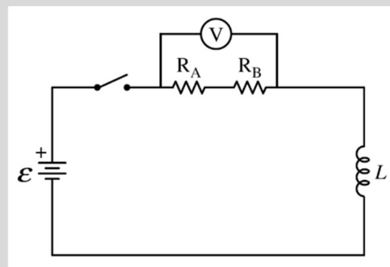
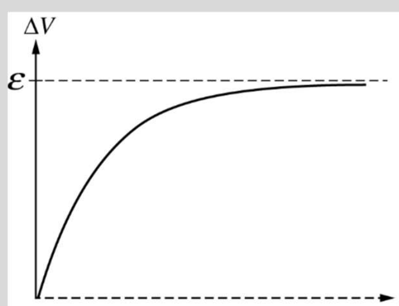
- Determine how to correctly connect a voltmeter to measure an increasing electric potential difference over time in an RL circuit that contains two identical resistors, an inductor, and a battery that are in series.
- Describe a procedure for using a voltmeter to collect data that allow for a graphically determined experimental value of the resistance of one resistor, based on a quantity that increases over time.
- Create a graph that represents the data collected.
- Explain how the information from the graph would be utilized to determine the experimental value of the resistance of one resistor.
- Using Kirchhoff's loop rule, derive, but do not solve, a differential equation to determine the current in the inductor at a given time after the switch is closed.
- Determine how changing the physical attributes of the inductor (i.e., adding resistance to an ideal inductor) would affect the electric potential difference across one of the resistors.

How well did the responses address the course content related to this question? How well did the responses integrate the skill(s) required on this question?

- While many responses correctly connected the voltmeter in parallel across one of the resistors, some responses incorrectly placed the voltmeter across the inductor. A few responses incorrectly suggested connecting the voltmeter in parallel with a wire or in series within the circuit.
- Many responses did not provide a procedure for collecting data using the specified equipment, and, instead, added unlisted supplies. These responses often attempted to use an ammeter or multimeter to collect data, particularly the current in the circuit. Additionally, some responses suggested using the voltmeter to measure the current in the circuit. The prompt explicitly stated that the provided voltmeter was for measuring electric potential difference as a function of time. Many responses failed to outline a procedure for data collection, opting instead to describe circuit behavior post-switch closure, often exclusively supported by equations.
- While many responses accurately depicted the concave-down and increasing exponential nature of the ΔV vs. t graph, some responses showed a concave-up and decreasing to zero curve. Additionally, a few responses incorrectly used a ΔI vs. t graph even though current could not be measured in the circuit. Furthermore, several responses failed to label the horizontal asymptote correctly. In addition, many responses did not demonstrate an understanding of the exponential nature of an RL circuit and attempted to create linear graphs, often resembling Ohm's law, with "V" and "I" on the axes.
- Several responses incorrectly suggested using the slope of an exponential graph to determine the experimental value of the resistance of one resistor. However, few responses correctly noted that the best-fit curve should be an exponential function. Some responses correctly demonstrated an understanding of this concept or mentioned using the time constant for the exponential graph.
- The majority of the responses exhibited an understanding of Kirchoff's loop rule; however, many responses did not include a derivation of more than one line. Several responses tried to integrate the given equation $\mathcal{E} = -L\dfrac{dI}{dt}$ from the formula sheet to calculate the current in the RL circuit at a time t after the switch was closed. Additionally, several responses failed to express their answers in terms of R, $\mathcal{E}$, L, and t.

- When comparing the electric potential difference across a resistor in series with an ideal inductor to the situation in which a resistor is in series with a nonideal inductor (one with nonnegligible resistance), most responses showed comprehension that the additional resistance in series would increase the total resistance of the circuit, and thereby decreasing the current and consequently reducing the electric potential difference across the resistor. Many responses also acknowledged that with the electric potential difference across the inductor increasing due to the addition of resistance, the electric potential difference across the original resistor must decrease.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Given an RL circuit in series and a voltmeter, responses indicating that there is a lack of understanding with the following: o The only quantity that can be measured that increases in value with time is the electric potential difference across the resistor(s). o A voltmeter must be connected in parallel to the resistor(s) to measure an electric potential difference. o A voltmeter is not a multimeter and cannot measure the current in the circuit as a function of time.	• Responses connect the voltmeter in parallel across the resistor(s) to correctly measure a potential difference that increases with time. 
• It was common for responses to demonstrate a misunderstanding that procedures for data collection should outline the actions a student would take to collect data rather than the subsequent steps for data analysis. For instance, stating, "The students should create a graph of ΔV vs. t" as a procedure addresses data analysis, not data collection. A proper procedure should focus on the process of obtaining the data.	• Responses regarding the procedure should outline that, with the provided circuit, a student is to connect a voltmeter in parallel across the resistor(s), then proceed to close the switch. Subsequently, using the voltmeter, they should record the potential difference as a function of time until steady-state conditions are reached.
• Not including labeled axes on a graph was common. • Not clearly showing asymptotic behavior and not labeling the asymptote was common.	• 
• When explaining the analysis of a graph, responses do not indicate the most suitable functional best-fit curve, either in words or with equations.	• The best-fit curve is an exponential function described by $V_R = \mathcal{E}\left(1 - e^{-\frac{2R}{L}t}\right)$.

• In many cases, responses aimed at graphical analysis intended for solving for a particular variable simply substitute data point values from the graph into equations.	• Rather than substituting data points, responses should focus on utilizing a feature from the determined best-fit curve. With the values of $\mathcal{E}$ and L established, *7* can be computed by utilizing the coefficient associated with the t term in the best-fit equation.
• Derivations do not begin from first principles and do not use multiple steps. • Responses do not adhere to accepted variables when substituting into derivations, introducing alternative variables. • Responses try to solve the differential equation.	• Starting from Kirchhoff's loop rule: $\Sigma\Delta V = 0$ $\mathcal{E} - \Delta V_R - \Delta V_L = 0$ • Substituting known variables and equations: $\mathcal{E} - I(2R) - L\frac{dI}{dt} = 0$ • When given "derive, but do NOT solve, a differential equation," the response should present the differential equation in a form that is ready for solving, avoiding the need for further algebraic manipulations: • Setting up the differential equation: $\mathcal{E} - 2IR = L\frac{dI}{dt}$ $\frac{1}{L}(\mathcal{E} - 2IR) = \frac{dI}{dt}$
• Responses overlook key details in the prompt. Many responses failed to recognize that the task is to compare the electric potential difference across a resistor in a circuit with a nonideal inductor to the situation in which an ideal inductor is used; responses, instead, provided answers that aligned with comparing the electric potential difference across the ideal and nonideal inductors. • Some responses incorrectly suggest that the electric potential difference across a resistor increases when the total resistance of a circuit increases and the battery emf remains the same.	• After reaching steady-state conditions, the electric potential difference across a resistor decreases when a nonideal inductor replaces an ideal inductor. With the nonideal inductor introducing resistance, the total resistance of the circuit increases. Consequently, as the battery emf remains constant, according to Ohm's law, the current in the new circuit decreases. Given that the current in the resistor decreases while the resistance remains unchanged, the electric potential difference across a resistor is smaller when in series with a nonideal inductor as compared to an ideal inductor.

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

- Ensure that only equipment listed in the provided list is used in the experimental procedure.
- When asked to write a differential equation for a circuit, begin with Kirchhoff's loop rule, then clearly illustrate the substitutions. If instructed to "derive, but do NOT solve, a differential equation," stop after determining the algebraic manipulation of the differential equation.
- Ensure that answers accurately and fully address the prompt.
- Verify if all quantities in a symbolic answer are permissible; confirm they are included in the "Express your answers in terms of" list.
- Review a "justify your answer" response to ensure it addresses the question posed.

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

- Teachers should direct students to the AP Daily videos on electric circuits, Kirchhoff's loop rule, Ohm's law, and RL circuits.
- Teachers should assign topic questions as well as personal progress check items to monitor progress being made in the mastery of content.

Question 3

Task: Short Answer
Topic: Electromagnetic Induction
Max Score: 15
Mean Score: 6.78

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Graphically determine how the absolute value of a magnetic flux through a square loop changes with time as the loop moves with a constant speed into a region that contains magnetic fields of different magnitudes.
- Determine and justify the direction of induced current in the resistor of the square loop due to a changing magnetic flux.
- Derive an expression for induced current in the resistor of the square loop by using Faraday's law and Ohm's law.
- Derive an expression for the power dissipated through the resistor of the square loop due to an induced current.
- Compare and justify the differences in energy dissipation by the resistor of the square loop that is moving through different magnetic fields.
- Graphically represent the induced current in a triangular conducting loop that is entering a magnetic field.

How well did the responses address the course content related to this question? How well did the responses integrate the skill(s) required on this question?

- Correctness of the responses for the graph of magnetic flux vs. position varied widely. Often, a response would earn some points, but did not show a complete understanding of magnetic flux. Very few responses got all of the points. Most often the errors were at the transition between magnetic field regions.
- Approximately half of the responses identified the correct direction of the induced current, and most of the responses providing the correct direction were able to correctly justify the selection. There were also many responses that did not identify the correct direction but did have the correct explanation for the correct direction.
- Most of the responses attempting to derive the equation for the induced current were successful. For the unsuccessful responses, most responses did not start with Faraday's law. The scoring guidelines require derive responses to start with a fundamental equation, and to use the fundamental equation in a derivation. Therefore, while many responses wrote down Ohm's law, the responses did not earn any points if nothing further was done with it.
- Most of the responses attempting to derive the equation for the induced current were also able to derive the correct equation for the power. The biggest problem for the incorrect responses was incorrect algebra.
- Few responses were able to determine the energy dissipated. Most responses that selected the correct answer were not able to correctly articulate why that answer was correct.
- Very few responses were able to successfully graph the induced current in the triangular 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*
• There is a difference between magnetic flux and the change in magnetic flux, and the implications of the difference between the two concepts should be considered.	• When graphing magnetic flux as a function of position, the magnetic flux should increase at a constant rate as more of the magnetic field is within the loop. Therefore, as the area of the loop enters the magnetic field at a constant speed, the graph should be linear with a constant slope. When moving entirely in a magnetic field of constant magnitude, the magnetic flux will remain constant as the change in magnetic flux is zero.
• There is a difference between magnetic flux and magnetic field. For example, incorrectly stating that a loop entering a magnetic field result in an increase in the magnetic field within the loop.	• A constant magnetic field through a changing area will result in a change in magnetic flux.
• When applying Lenz's law, a generic statement that changing magnetic flux will result in a current but not carefully specifying whether the magnetic flux increases or decreases and whether the current is clockwise or counterclockwise makes it difficult to show mastery of content.	• Consider specific claims such as, "The direction of the change of the magnetic flux is into the page, which results in an induced emf, which results in a counterclockwise current."
• Incorrectly using Ampere's law to determine the induced current in the loop.	• Begin with Faraday's law to determine induced current due to a changing magnetic flux.
• Responses often did not recognize that the change in area as the loop moves into the magnetic field is a function of the length of the wire and the speed with which the wire is moving.	• Consider that $\frac{dA}{dt} = Dv$.
• In part (c), responses included an incorrect justification that stated that the change in area does not affect the energy dissipated.	• The loop encounters the same changes in magnetic flux as the loop crosses the transitions in both scenarios.

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

- Provide students task models in which they can practice identifying best-case justifications; allow the students to view examples of generic and specific justifications, and then require the students to select which justifications are best and why the justifications are best.
- Provide students with multiple items in which the students graph the value of the magnetic flux through a loop as the loop enters a field; examples should include situations in which the magnetic flux changes for various reasons and how the change in magnetic flux results in changes to the power dissipated by a resistor or a conducting loop. Students can then compare and contrast the graphs.
- Allow students to practice deriving more complex expressions and equations by beginning derivations from fundamental equations and concepts. Remind students that derivations must be multiple steps that logically proceed from one step to another step.

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

- Teachers should direct students to the AP Daily videos on electromagnetic induction, Faraday's law, and Lenz's law.
- Teachers should assign topic questions as well as personal progress check items to monitor progress being made in the mastery of content.