Chief Reader Report on Student Responses:

2024 AP® Physics Electricity and Magnetism Set 1

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: Electric Potentials and Fields
Max Score: 15
Mean Score: 6.14

What were the responses to this question expected to demonstrate?

- Responses should demonstrate comprehension of the concepts of electric flux and its relationship to charge and Gauss's law.
- Responses should demonstrate the ability to determine electric field given information about electric potential and vice versa.
- Responses should demonstrate comprehension of the connection between electric potential, charge, and energy/work.
- Responses should demonstrate comprehension of equipotential lines or surfaces and ability to interpret a diagram illustrating equipotential lines.
- Responses should demonstrate the ability to use charge density to derive an expression for the potential or electric field as a function of position relative to a charge distribution.
- Responses should be able to produce a graph of potential vs. position for a given charge distribution.
- Responses should demonstrate the ability to choose appropriate fundamental equations, derive appropriate expressions including substitutions of given variables, and calculate results with correct numerical values and units.
- Responses should demonstrate the ability to make a claim and justify using physics principles.

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?

- Although many responses showed familiarity with Gauss's law to determine the electric field, a small number used it to determine electric flux through a surface enclosing a given charge. For responses that could determine electric flux, many were unable to give the correct units.
- Most responses were able to make correct quantitative comparisons of the work done to move a charge through a given map of equipotential lines.
- Although many responses demonstrated a familiarity with using $E = \frac{dV}{dx}$, a small number of responses were able to read approximate values from the equipotential map with enough accuracy to calculate a reasonable value for the electric field. Many responses did not correctly use the given distance scale increments of 0.40 m.
- Most responses were able to correctly identify and qualitatively describe the direction of electric force on a test charge placed in a given charge distribution and equipotential lines.
- For the prompt in part (c) with a check box and justification, it was clear by the justifications given in many responses, that *multiple* choices for direction of the force *could* and *should* be selected instead of *only one*. The responses then proceeded to give logical rationales for the multiple selections.
- In the justification for part (c), most responses demonstrated clear understanding that opposite charges attract, like charges repel, and that an electric force exerted on a positive charge is in a direction toward a lower electric potential. However, few responses correctly stated that the electric field and force must be directed in a direction perpendicular to an equipotential line.
- For part (c), although the prompt asked for the electric force at the instant of release, many of the response justifications described the path the test charge would take after it accelerated away from the equipotential line.
- Not many responses showed the ability to correctly set up an integral to determine the electric potential produced by a uniform line of charge. Approximately half of the responses attempted to determine the potential by starting with the equation that shows the potential difference as an integration of electric field over a given path. Though it is possible to take this alternate approach, it is quite a bit more challenging, and very few responses were able to earn full credit taking this approach.

- Quite a few responses seemed to "reverse engineer" the derivation of the given expression by understanding that only an integral with "$\frac{1}{x}$" would yield a result with the natural logarithm of x that appears in the expression. Many of these responses were able to earn one or more points without clearly demonstrating an understanding of the physics involved.
- Most responses were able to correctly sketch a graph of potential vs. position showing an approximation of the nonlinear decrease in magnitude with increased distance from the charge distribution.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Electric field is the same as electric flux. Example solution to part (a), which asks for electric flux: $EA = \frac{q}{\varepsilon_0}\ E\left(4\pi \cdot 0.5^2\right) = \frac{2\times10^{-9}}{8.85\times10^{-12}}$ $E = \frac{2\times10^{-9}}{8.85\times10^{-12}\left(4\pi\cdot0.5^2\right)} = 72\ \frac{\text{N}}{\text{C}}$ • Response appears to mistake electric field for electric flux.	• Electric flux is a product of field and area, and it can be equated with charge divided by the permittivity constant (by Gauss's law): $\Phi_E = \oint E\cdot dA = \frac{q}{\varepsilon_0} = \frac{2\times10^{-9}}{8.85\times10^{-12}}$ $\Phi_E = 226\ \frac{\text{Nm}^2}{\text{C}}$
• When using a grid to determine a value, it is best to go with the nearest gridline as the best estimate. $E_x = \frac{\Delta V}{\Delta x} = \frac{20-0\text{ V}}{2(0.4\text{ m})} = 25\ \frac{\text{V}}{\text{m}}$ • Note: This response earned all points in spite of this lack of precision.	• When determining a value that falls between gridlines it is best to give an estimated value that falls between the known values shown by the gridlines. $E_x = \frac{\Delta V}{\Delta x} = \frac{20-0\text{ V}}{2.47-1.79} = 29\ \frac{\text{V}}{\text{m}}$

• An integral in electrostatics can be determined by simply plugging in a representative equation for the integrand and applying the correct antiderivative rule from calculus. $\Delta V = -\int E \cdot dr$ $V_P = -\int \frac{kq}{r^2} dr = -\int \frac{k(\lambda r)}{r^2} dr$ $V_P = \int_{x_P-4L}^{x_P} \frac{k\lambda}{r} dr = k\lambda \ln\left(\frac{x_\text{P}}{x_\text{P} - 4L}\right)$ Note: This incorrect solution appeared in many responses and the mistakes made were likely reinforced by the fact that the prompt gave the correct answer for the students to derive. Many responses appeared to reverse engineer the desired expression.	• An integral in electrostatics represents an infinite sum, and it is necessary to represent infinitesimal quantities of charge dq in terms of charge density and the chosen variable of integration. $V_\text{P} = \int \frac{kdq}{r} = \int \frac{k\lambda dr}{r}$ $V_\text{P} = \int_{x_\text{P}-4L}^{x_\text{P}} \frac{k\lambda dr}{r} = \ln\left(\frac{x_\text{P}}{x_\text{P} - 4L}\right)$

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?

- Before introducing and using Gauss's law, spend time and work examples calculating electric flux as the integral of electric field and area.
    - For a student to truly understand Gauss's law it is important to really understand the abstract concept of electric flux. Introduce flux by using more concrete illustrations. For example, ask the classic question: should you walk or run in the rain? The quantity of rain that you encounter is a product of "rain flow" and cross-sectional area. Another example is solar energy—the rate of energy production (power) of a solar panel is proportional to the dot product of solar constant $1340\ \frac{\text{W}}{\text{m}^2}$, area, and normal vector.
    - Another very useful way to understand flux is the idea that it is proportional to the number of electric field lines passing through a surface. Again, many parallels can be made with the concrete examples of rain and light.
    - Assign homework problems that are concerned *only* with determining electric flux with no mention or use of Gauss's law. This encourages students to think about the concept and hopefully internalize it.

- Show work for any integration problem by starting with the most general form of the integral and showing successive simplifications and substitutions step-by-step.
    - When it comes to integrals, such as the calculation of electric potential, it is important to work with lots of examples, explaining each part of the process. Many integrals like potential have an infinitesimal element (dq) that typically needs to be put into terms of the relevant variable for the purpose of integration. Stress with many examples that it is necessary to identify a single variable for the integrand and then make an appropriate substitution for the infinitesimal element in terms of this same variable. In this particular question, the potential varies with respect to distance r from the given position x_P and the element dq is written as λdr.
    - It is also important to give students adequate opportunities to practice and repeat this process by themselves. The same basic process is used to find the center of mass and moment of inertia in Mechanics, and electric field, potential, magnetic flux, and several other quantities in Electricity and

Magnetism. After practice with these topics, students should become comfortable with the technique. Students should be asked to evaluate integrals like these during class time practice and on homework assignments on a regular basis.

  - Emphasize the importance of “setting it up” much more than the actual evaluation of the integral. Setting it up correctly requires comprehension and application of physics. Emphasize an integral is an infinite summation and point out the significance to each scenario. In this question, point out that the total electric potential at position x_P is an infinite sum of quantities of potential contributed by pieces of charge at varying distance. It is necessary to integrate because the amount of potential from each infinitesimal “piece” of the line of charge is different due to the variable distance of each piece from the position x_P .
  - Another helpful point of emphasis is to always make a diagram of the infinitesimal element such as dq .

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 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: LR Circuit
Topic: Experimental Design
Max Score: 15
Mean Score: 5.11

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Calculate the equivalent resistance of a parallel circuit.
- Determine the potential difference across an inductor in a LR circuit at $t = 0$ and $t = \infty$.
- Identify the placement of a voltmeter to illustrate a decreasing potential difference over time as the inductor is energized.
- Apply Kirchhoff's loop rule to an LR circuit.
- Graphically model the behavior of an LR circuit to determine a best curve-fit to the data chosen.
- Derive an expression for the resistance in an LR circuit based on experimental data and a known inductance value.
- Sketch a graph that shows a functional relationship between potential difference and time across an inductor in a LR circuit.
- Select and plot data from an experimental procedure to represent a decreasing measured quantity.
- Linearize exponential data and/or determine the best-fit curve of exponential data.
- Determine and justify the relationship between the voltages of an ideal inductor and an inductor with internal resistance.

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?

- Responses indicated difficulty in determining which components of an LR circuit experiences a decreasing potential difference when charging and discharging occur.
- Many responses incorrectly showed an analysis of data in addition to or instead of a procedure.
- Many responses correctly indicated potential or potential difference for the inductor vs. time graphs.
- Most responses correctly stated a procedure that includes recording at least one potential difference measurement.
- Few responses stated a correct procedure for continually collecting data until the initial time constant (τ) or steady-state conditions are met.
- Some responses incorrectly showed a decay curve when placing the voltmeter in parallel with the resistor.
- Most responses correctly had "potential difference" (or potential) and "time" as labels for the vertical and horizontal axes.
- Some responses incorrectly indicated the graph does not asymptotically approach zero when the voltmeter was correctly placed across the inductor.
- Most responses correctly indicated the asymptotic approach to $\mathcal{E}$ when the voltmeter was *incorrectly* placed across the resistors in parallel. In this case, consistency points could be earned.
- Roughly two-thirds of responses correctly labeled the asymptote.
- Responses tended not to correctly state that the switch must be closed before data collection occurs.
- A small number of responses correctly linearized the data on the graph although this did not need to be done.
- Most responses correctly attempted to derive a differential equation starting with an appropriate application of Kirchhoff's loop rule.
- Three-quarters of responses correctly indicated an inductor with internal resistance would have a higher potential difference when compared to an ideal inductor (one without internal resistance).
- Of the responses that correctly stated an inductor with internal resistance would have a larger potential difference in comparison to an ideal inductor, the vast majority justified the claim with correct reasoning.
- Few responses correctly stated that an inductor with no internal resistance would have zero potential difference when the LR circuit reached steady-state conditions.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Placing a voltmeter in parallel across a resistor in an LR circuit to measure a decreasing quantity after the switch is closed.	• Place a voltmeter in parallel across the inductor (not resistor) to obtain a potential difference vs. time graph with a corresponding concave-up and decreasing curve.
• Data is recorded by the voltmeter.	• Recording potential difference data across the inductor. ○ Close the switch. ○ Record the potential difference value at each time increment. ○ Continuously collect data until the initial time constant or steady-state conditions are met. ○ Plot a graph of potential difference across the inductor vs. time.
• Analysis of data is provided when asked for procedure.	• Provide an experimental procedure. ○ Create a circuit as shown in Figure 1. ○ Open the switch. ○ Connect and turn on the voltmeter in parallel across the inductor. ○ Start a timer when the switch is closed. ○ Record the potential difference across the inductor every second until steady-state conditions are met.
• Providing the final derived differential equation for current without showing work.	• Write out Kirchhoff's loop rule for the LR circuit using subscripts for each component ($\mathcal{E} - \Delta V_{R_{\text{eq}}} - \Delta V_L = 0$) • Find the equivalent resistance and correct expression for the potential difference across the inductor. • Substitute the expressions for the potential difference across the resistors and inductor into the Kirchhoff's loop rule equation.

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?

- Use LR circuit simulations (e.g., https://www.geogebra.org/m/qxydsrrs) to explore LR circuits.
- Utilize College Board YouTube videos such as 2022 Live Review 8 | AP Physics C: E&M | RC, LR, and LC Circuits (https://www.youtube.com/watch?v=T9cH0BscXtY).

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 LR 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: Magnetic Flux and Induction
Max Score: 15
Mean Score: 6.41

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Graphically represent the magnetic flux for a square loop of wire as it enters a region containing a single magnetic field and then a region containing two magnetic fields in opposing directions.
- Determine and justify the direction of induced current due to a changing magnetic flux.
- Derive an expression for induced current in a square loop of wire using Faraday's law and Ohm's law.
- Derive an expression for power dissipated by a resistor due to an induced current.
- Compare and justify the differences in energy dissipation for a moving loop of wire through a different scenario of magnetic fields.
- Graphically represent the induced current due to a triangular loop of wire entering a uniform 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?

- Many responses earned nearly all of the points in the initial flux graph; however, responses earning fewer points either misinterpreted spacially where flux was present or graphed change in flux vs. position instead of magnetic flux itself.
- Nearly all responses correctly determined the direction of induced current in the wire loop, however justifications often provided a general explanation of Lenz's law rather than stating the specific directions of induced fields or change in flux.
- Most responses properly applied Ohm's law to determine induced current, but many responses did not explicitly state Faraday's law to begin the multistep derivation. Additionally, many responses did not recognize that the length of the wire causing an induced current is $2L$.
- Nearly all responses correctly stated an equation for power and made proper substitutions for current using the provided quantities.
- Many responses selected the proper comparison for energy. However, few responses successfully justified the reason for the difference in energy, noting that the important feature is the change in flux decreasing rather than the magnetic flux itself.
- Most responses successfully graphed the increase in the current as the triangle entered the field. However, once the change in flux became constant, some responses graphed the current as a constant nonzero value due to misinterpreting flux instead of change in flux.

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 response does not appear to differentiate between magnetic flux and <u>change</u> in flux.	- When graphing flux as a function of position, the 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 field at a constant velocity, the graph should be linear with a constant slope. Upon entering a region of constant magnetic field, the flux will remain constant as the change in flux is zero.
- The response does not appear to differentiate between magnetic flux and magnetic field. For example, stating that a loop of wire entering a field is an increase in the magnetic field within the loop.	- A constant magnetic field with a changing area will result in a change in flux.
- When applying Lenz's law, a generic statement that changing magnetic flux will cause a current, but not carefully specifying whether the flux increases or decreases and whether the current is clockwise or counterclockwise.	- The direction of the magnetic flux change is into the page, resulting in an induced emf, which causes a counterclockwise current.
- Responses to a derive prompt do not start with first principles, and do not show all the steps to the final response.	- Starting with Faraday's law as stated and working through $\frac{d(BA)}{dt}$ to arrive at the resulting equation for emf to be $2BLv$.
- In part (c), responses stating that a smaller change in flux results in a smaller emf.	- The area of the loop enters the field at the same velocity, resulting in the same rate of change of flux and thus the same emf. However, due to the new area containing a net magnetic field being smaller, the loop experiences the emf for shorter time and thus less energy.

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?

- When planning for the year, ensure enough time to teach electromagnetic induction and work through mathematical and conceptual problems.
- When graphing magnetic flux, have students draw the graphs for magnetic flux, change in magnetic flux, and emf. Finally, make comparisons of the relationships between the graphs.
- Compare the difference between changing magnetic flux and induced magnetic field as it relates to Faraday's law.
- Practice derivations beginning from fundamental equations on the equation sheet. While shortcuts may be convenient, using a unique case equation undermines building this skill.
- When working multi-part problems, score student papers, giving credit for consistency with prior work.
- Present three different justifications for a given response for students to evaluate the differences in quality. One simple, one generic, and one that uses specific language for the given case (the best case). For future justifications, use a rubric, noting specific language that should be present.

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 magnetic flux and induction.
- Teachers should assign topic questions as well as personal progress check items to monitor progress being made in the mastery of content.