Chief Reader Report on Student Responses:

2023 AP® Physics C: Electricity and Magnetism Set 2

Free-Response Questions

- Number of Students Scored: 24,179
- Number of Readers: 624 (for all Physics exams)
- Score Distribution

Exam Score	N	%At
5	8,126	33.61
4	5,674	23.47
3	3,176	13.14
2	4,329	17.90
1	2,874	11.89

- Global Mean: 3.49

The following comments on the 2023 free-response questions for AP® Physics C: Electricity and Magnetism were written by the Chief Reader, Brian Utter, teaching professor and associate dean of general education at the 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: Experimental Design
Topic: Electrostatics: Charge and Coulomb's Law
Max Score: 15
Mean Score: 7.64

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Draw a free-body diagram indicating the forces exerted on a nonconducting, positively charged sphere hanging from a string near another positively charged sphere.
- Derive the relationship between the distance between two charged spheres and the angle θ of the string to validate a given expression for distance in terms of θ, requiring the application of Newton's second law in two dimensions.
- Calculate the tension in the string using an appropriate application of Coulomb's law.
- Draw a best-fit line that shows the trend of given data.
- Calculate the slope of the best-fit line and use the slope to find an experimental value of permittivity.
- Draw a representation of polarization on a sphere.
- Explain how charges move on a conducting sphere when near another charged sphere.
- Describe the motion of a charged conducting sphere when near another charged sphere.

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?

- Nearly all responses were able to identify the correct forces and their respective directions that were exerted on Sphere 2; however, many responses did not label the electric force as F_E, instead writing a nonconventional label that does not clearly indicate the source of the force.
- Many responses started the derivation with the horizontal and vertical net force equations and clearly showed an attempt to solve these equations simultaneously to calculate the tension force. A large number of responses "reverse engineered" their answer by starting their solution with an algebraic manipulation of the provided expression. This method did not show a clear understanding of applying an appropriate analysis of Newton's second law.
- Nearly all responses correctly applied Coulomb's law in an appropriate equation for tension. However, many responses failed to show the numerical substitutions for the symbolic quantities in their expression to show how their final answer was calculated.
- Nearly all responses were able to draw an appropriate line of best fit for the data given.
- Most responses were able to calculate the slope of their line, but some responses neglected to show the two points used from their best-fit line in their calculation.
- Most responses successfully connected their slope value to the corresponding expression to calculate an experimental value for permittivity.
- Nearly all responses successfully drew a "+" on the left side of Sphere 3 and correctly explained polarization and charge distribution within a conductor.
- Many responses successfully selected an angle comparison consistent with their drawing in part (e)(i); however, some responses did not justify their selection with a connection to the change in electrostatic force.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Labeling the forces using nonconventional variables; for example, electrostatic force as F_a or F_S (where the "s" may stand for sphere, but has not been defined), tension force as L or F_S (where the "s" may stand for string, but has not been defined), gravitational force as g.	• On a free-body diagram of the system at equilibrium, there are three forces represented. The force of gravity is directed downward, the force of tension is directed upward and to the left, and the electrostatic force is directed to the left. All vectors begin from the dot and point outward and have appropriate labels.
• Trying to derive the expression provided by starting with the final answer and working backward.	• Begin with Newton's second law and resolve into two equations that sum the forces in the x- and y-directions, respectively. Then use simultaneous equations to eliminate the force of tension and solve for d.
• Not showing work in the calculation involved for getting an experimental value of permittivity and the mass of the sphere, for example: o Not showing what two points are used to calculate slope; o Not showing explicitly how the slope is related to the expression used for the final calculation; and o Not substituting all numerical values into the final expression.	• Showing an expression that contained substituted values before the final calculation answer, particularly if there was something that might have been typed incorrectly into a calculator.
• Assuming that charges are equally distributed across the surface of a spherical conductor.	• Placing Sphere 3 near Sphere 2 causes the charge to polarize on Sphere 3. The charges on Sphere 3 rearrange to attract opposite charges and repel like charges. The positive charges are on the left.

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?

- When creating a line of best fit, have students draw a line that corresponds with the data points rather than draw a line that includes the point $(0,0)$. The y-intercept may be nonzero and have physical meaning. The slope of the line of best fit is often necessary for further calculations, derivations, or is a means to make sense of a concept. Cutting corners here could hinder future progress.
- When finding the slope of a best-fit line, clearly show the two points from the best-fit line used. Do not choose data points not on the line, instead choose two points on the line, which may not correspond to data points.
- When asked to derive a final expression that is provided to the student, do not start with the final expression, and attempt to work backwards.
- Before calculating a final answer, explicitly substitute all numerical values into the expression.

- Identify the slope of the best-fit line in the expression for the permittivity constant.

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 from Unit 1.
- Teachers should direct students to Higher Ed Faculty Lectures on Unit 1.
- 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: Short Answer
Topic: Magnetic Induction
Max Score: 15
Mean Score: 5.72

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Determine the direction of the induced current in a conducting rod and the magnetic force on in the conducting rod that is moving through external magnetic fields for a closed loop.
- Solve problems based on the concepts of magnetic induction, including applications of Faraday's law, Lenz's law, and the magnetic force equation.
- Sketch a graph of velocity vs. time for
    - an object affected by a constant (or zero) force;
    - an object affected by a variable force that is dependent on velocity; and
    - an object affected by a variable force that is dependent on position, i.e., the force from an ideal spring.
- Determine the equivalent resistance of a network of resistors.
- Apply Ohm's law both numerically and qualitatively to determine and/or analyze current.
- Determine qualitatively the effect of changes in current on magnetic force acting on a current-carrying wire.
- Determine qualitatively the effect of changes in force/mass on magnitude of acceleration.
- Make a claim and justify the functional dependency of B, L, or v on the magnitude of the potential difference across a conducting rod moving through an external uniform magnetic field.

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 responses incorrectly predicted the direction of the resulting magnetic force on a rod due to the increasing magnetic flux through a closed conducting loop.
- A significant number of responses that could not successfully quantitatively apply Faraday's law to solve for the induced emf and resulting current in the rod were able to qualitatively describe Faraday's law and correctly justify how changes in B, L, or v related to the change in magnetic flux and induced potential difference.
- Most responses were unable to correctly sketch the velocity versus time graph for an object experiencing a force from an ideal spring.
- Of the few responses that correctly identified the direction of the resultant magnetic force on the rod, even fewer correctly sketched the velocity-time functional dependency while in the magnetic fields.
- Most responses incorrectly indicated a change in the velocity of the rod when the rod transitioned across the opposing magnetic fields.
- Most responses correctly determined the equivalent resistance of a circuit when resistive elements were arranged in parallel.
- Many responses failed to indicate proper units when determining the equivalent resistance.
- Most responses were able to correctly identify the inverse relationship between resistance and current.
- Most responses were able to correctly identify the direct relationship between current and magnetic force.
- A significant number of responses had little in the way of substantive solutions.

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 how forces can be determined either through applying Lenz's law or right-hand rules in determining currents and forces in a dynamic magnetic system.	• Responses were able to both correctly predict the net force on the moving rod by correctly determining the direction of the induced current and then predict the direction of the resulting magnetic force on the conducting rod.
• Not understanding that a change in the direction of the magnetic field does not automatically cause a change in the magnetic force.	• Responses correctly kept the direction and magnitude of the magnetic force constant as the orientation of the external magnetic field changed by 180 degrees.
• Not understanding that Ampere's law does not apply to electromagnetic induction for changing magnetic flux in relating magnetic fields to currents.	• Responses correctly use Faraday's law in developing a relationship between the change in magnetic flux and the induced emf.
• Not understanding how a time-varying force affects the shape of velocity versus time graphs.	• Responses correctly drew, with correct concavity, the velocity versus time graph for an object pushed by an increasing force from rest and for an object pushed by a decreasing force.
• Not being able to properly justify how a system responds to physical changes.	• Responses correctly and specifically address all functional dependence.

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?

- Physically demonstrate Lenz's law to students so they can obtain a better understanding of how the principle applies to predicting the directions of currents and forces due to electromagnetic induction.
- Whenever students are using Lenz's law to predict the direction of the induced current in a closed conducting loop, have them also draw the direction of the forces on different portions of the loop and the direction of the induced magnetic field.
- Whenever students are drawing graphs, ask them to discuss or justify the physical significance of the slope, intercept, and area under the curve.
- Students should write justifications that are specific and address relevant changes to the situation.
- Require students to regularly write logically connecting explanations with physics content when they need to justify their responses.
- Stress to students that electromagnetic induction is due to changes in *flux*, as stated by Faraday's law, not simply changes in a magnetic field.
- Review the equation sheet with students, making sure that they understand each of the physical quantities that the symbols represent in each formula while emphasizing that those same symbols may be used to represent other unrelated physical quantities within the context of specific questions. For example, L used to represent length in a specific question being confused with inductance on the formula sheet.

- Discuss with students what reasonable magnitudes of physical quantities to expect so that they can identify obvious errors in their own solutions when presented with quantities that are of unreasonable magnitude for a given situation.

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 from Unit 5.
- Teachers should direct students to Higher Ed Faculty Lectures on Unit 5.
- 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: Circuits
Max Score: 15
Mean Score: 4.58

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Apply Kirchhoff's Loop Rule (conservation of energy) in a complex RC circuit.
- Use Ohm's law and the definition of capacitance for individual circuit elements.
- Graphically represent the time dependence of quantities in an RC circuit.
- Predict short-term and long-term behavior of an RC circuit while capacitors are charging and discharging.
- Apply conservation of energy to a circuit problem to determine energy dissipation or power used by a circuit element.
- Calculate how changing the physical attributes of a capacitor (e.g., plate separation distance or the presence or absence of a dielectric) would affect the electric potential energy stored in the capacitor.

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?

- Many responses did not understand what a differential equation is or that applying Kirchhoff's Loop Rule was a necessary first step. Others did not stop after simply writing a differential equation as instructed but went on to attempt a solution.
- For numerous parts of the problem, many responses incorrectly started with a memorized solution for the charge or current in a generic RC circuit as a function of time.
- Most responses correctly sketched the graphs, although some responses were not careful to show clear asymptotic behavior as time increased.
- While many responses demonstrated an understanding that the capacitor with capacitance $2C$ would hold twice as much charge in steady state as the one with capacitance C, many ignored conservation of charge when finding the steady state charges on the system of two capacitors.
- When asked to find the energy dissipated in the resistors, some responses attempted to integrate the power dissipated in the resistors, a long and difficult solution, rather than find the difference in the initial and final electric potential energies stored in the capacitors.
- Most responses demonstrated the understanding that doubling the plate separation of a capacitor cuts its capacitance in half, but many did not realize that meant that the two capacitors had equal capacitance after the change because they overlooked the fact that Capacitor 2's original capacitance was $2C$. Retaining given information while doing the problem was difficult for many.
- When comparing the electric potential energies of Capacitors 1 and 2 (in the ratio U_2 / U_1), many responses focused on the role of only the capacitance in the potential energy, ignoring the fact that U depends on C and either Q or V as well.
- Some responses included quantities in their symbolic answers that were not permitted. For example, answers to part (e) often included the emf of the battery, even though that was not listed in the variables allowed in the final expression.

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 solution to a differential equation is NOT a differential equation. Many responses simply wrote a memorized solution to the differential equation for a generic RC circuit when the prompt asked them to write and not solve the differential equation.	• Responses started with a clear loop rule, included the equivalent resistance of the pair of resistors, and showed the substitution of dQ / dt for current.
• Graphs did not clearly indicate asymptotic behavior, and some were not monotonically increasing or decreasing.	• Responses showed a dotted horizontal line at a nonzero horizontal asymptote with an always increasing or always decreasing curve approaching that dotted line or the horizontal axis and continuing long enough that the asymptotic behavior was clearly indicated.
• Responses failed to provide sufficient evidence to justify the answer. In many cases they simply restated the claim or provided only part of the needed evidence. For example: ○ The current is *to the right because it flows clockwise around the circuit* (restated the claim). ○ The current is *to the right because it moves from the positive plate to the negative plate* (failed to indicate which plate is positive).	• Responses gave a clear indication of which capacitor plate would accumulate positive (or negative) charges or which would plate would be at higher (or lower) electric potential, which supported their answer about the direction of the current. For example: ○ *The direction of the current would be to the right because the positive charges would accumulate on the top plate of* C_1 *and when the switch is closed the current would be clockwise.*
• Responses treated the situation where an initially charged capacitor was connected to an initially uncharged capacitor as a proportional reasoning or ratio problem, ignoring the conservation of charge. These responses found resulting charges of Q_0 on Capacitor 1 and $2Q_0$ on capacitor 2 after the switch was moved to Position B.	• Responses recognized that the total charge remains Q_0 and the potential differences are equal after a long time, finding that the charge on the Capacitor 2 would be $2Q_0 / 3$, which is twice the charge on the Capacitor 1, $Q_0 / 3$.

- Responses overlooked physics concepts learned in mechanics class, such as the conservation of energy when solving a problem involving electricity and magnetism, such as finding the energy dissipated by the pair of resistors.	- Responses recognized that finding the energy dissipated in the resistors was equivalent to finding the difference in initial and final electric potential energies of the capacitors, rather than attempting to integrate a time-dependent function for the power used by the resistors, a much more time-intensive and difficult task.
- Responses indicate a lack of reading the prompt carefully. Many overlooked the fact that the capacitance of Capacitor 2 was given as $2C$ before the plate separation was increased.	- Responses addressed the fact that the capacitances of Capacitors 1 and 2 were equal after the plate separation distance of Capacitor 2 was increased because the capacitance of Capacitor 2 went from $2C$ to C.
- For an expression that depends on two quantities, responses only addressed how the expression depended on one of the two quantities, which was an incomplete answer. In this problem, responses treated the electric potential energy of a capacitor as if it only depended on capacitance, without mentioning the dependence of potential energy on stored charge or potential difference. For example, because C is proportional to $1/d$, doubling the plate separation distance halves the capacitance, which halves the electric potential energy.	- Responses discussed (implicitly in equations or explicitly in words) that both the capacitances were equal after the plate separation was doubled and that either the charge stored on each capacitor or the potential difference across each capacitor would be equal after a long time.
- Initial and final conditions are vital to the understanding of a physical situation. Responses relied upon memorized solutions for charge or current as a function of time, even when the prompt asked for a quantity “immediately after” a switch is opened or closed or for a quantity “after a long time.”	- Solutions for parts (c)(ii) and (d) recognized that after a long time, the potential difference across each capacitor would be equal. Responses for part (e) substituted the initial condition $\mathrm{E} = Q_0 / C$ into the loop rule because the prompt did not allow E to be in the answer.

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?

- For questions that ask students to write a differential equation, have students start with Kirchhoff’s Loop Rule, then clearly show the substitution of a derivative such as $I = dq / dt$. If the problem states, “Write but do NOT solve,” students should stop after the differential equation is determined.
- For questions that ask students to sketch curves with asymptotic behavior, make sure the curve is either always increasing or always decreasing and that it continues long enough to indicate the asymptotic behavior clearly.
  - For curves with nonzero horizontal asymptotes, have students draw a dotted horizontal line at the asymptote with the curve approaching that dotted line and continuing long enough that the asymptotic behavior was clearly indicated.
- Make sure answers respond correctly and completely to the prompt.
  - As a final step, ask students to:
    - Write units on numerical answers.

        - Check to see if all quantities in a symbolic answer are permitted. (Do they show up in the “Express your answer in terms of” list?)
        - Reread a “justify your answer” or “explain” answer to make sure it answers the question asked. If an expression depends on two or more quantities, address each of the quantities, even if one or more of them remains constant.

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 from Unit 3.
- Teachers should direct students to Higher Ed Faculty Lectures on Unit 3.
- Teachers should assign topic questions as well as personal progress check items to monitor progress being made in the mastery of content.