Chief Reader Report on Student Responses:

2025 AP® Physics C: Electricity and Magnetism Free-Response Questions

• Number of Students Scored	29,910		
• Number of Readers	840		
• Score Distribution	Exam Score	N	%At
	5	7,504	25.1%
	4	7,063	23.6%
	3	7,199	24.1%
	2	5,340	17.9%
	1	2,804	9.4%
• Global Mean	3.37		

The following comments on the 2025 free-response questions for AP® Physics C: Electricity and Magnetism were summarized by the Chief Reader, Brian Utter, Teaching Professor and Associate Dean of Undergraduate Education, 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: Mathematical Routines
Topic: Gauss's Law, Electric Potential Difference, Capacitance

	Max Points:	Mean Score:
A1	1	0.80
A2	1	0.40
A3	1	0.34
A4	1	0.66
A5	1	0.64
A6	1	0.35
A7	1	0.57
B1	1	0.26
B2	1	0.21
B3	1	0.19

Overall Mean Score: 4.43/10

What were the responses to this question expected to demonstrate?

The responses were expected to:

- Demonstrate understanding of electric flux and its relationship to the charge enclosed by a Gaussian surface
- Demonstrate awareness of the three different geometries (planar, spherical, and cylindrical) of symmetrically charged objects and the effect that each geometry has on the electric field produced by these distributions of charge
- Relate the electric potential difference to the electric field
- Indicate an understanding of the effect of adding a dielectric to a capacitor, including the weakening of the electric field, the reduction in the potential difference for an isolated, charged capacitor, and the increase in capacitance
- Indicate an ability to make qualitative sketches of graphs (linear, inverse, parabolic, and exponential), for instance for electric field as a function of position

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 most responses showed familiarity with Gauss's law to determine the electric field, many responses indicated a lack of understanding of the surface area of an appropriate closed Gaussian surface and the charge enclosed by this Gaussian surface. This includes a lack of understanding of the surface integral as compared to more familiar integrals along one direction. Common errors included:
  - Responses that inadvertently calculated the volume of the Gaussian surface, or responses that used the volume of the inner shell of the capacitor to determine the enclosed charge
  - Responses that used a variety of distance values for the radius r of the Gaussian surface as well as the correct location of the charge enclosed by the Gaussian surface (at radius R_1)
  - Responses that neglected to include the length of the capacitor when determining the surface area of the Gaussian surface and/or the charge enclosed by the Gaussian surface
  - Responses that confused surface area with cross-sectional area
  - Responses with nonzero values in part A (iii) for both regions $r < R_1$ and $r > R_2$, which indicates a misunderstanding of the either the purpose of a Gaussian surface and/or the charge enclosed by it
  - Responses that demonstrated a lack of understanding of charge density to determine the charge enclosed by the Gaussian surface (including the differences among linear, area, and volume density, and in some cases, the meaning of density)

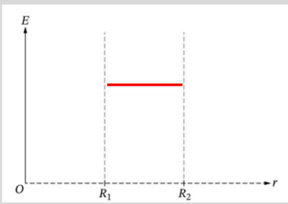
- Instead of using Gauss's law a significant number of responses attempted to use an infinitesimal element of charge (dq) of the inner shell of the capacitor to determine both the electric field as a function of r in the region $R_1 < r < R_2$ and the potential difference between radii R_1 and R_2.
- In the responses that did show the correct relationship between potential difference and electric field, the most common errors included:
  - Responses that made a substitution for the electric field, E, from part A (i) while simultaneously integrating the expression, perhaps incorrectly, in one step without showing each action separately
  - Responses that replaced the unspecified radius r of the cylindrical Gaussian surface with a combination of values that included R_1, R_1, and/or r_1 when substituting the expression determined in part A (i) into the integral equation in part A (ii)
  - Responses that indicated an inability to correctly integrate and/or neglected limits of integration.
- A significant number of responses indicated minimal connection between parts A (i) and A (iii). For example, an abundance of responses that had the correct dependence of the electric field as a function of $1/r$ for $R_1 < r < R_2$ in part A (i), had linear or parabolic sketches in part A (iii).
- For Part B only around a quarter of responses indicated correct responses. A significant number of responses simply used the equation for parallel plate capacitance, $C = \dfrac{\kappa \varepsilon_0 A}{d}$, as provided on the reference sheet. The use of this equation indicates a lack of understanding of the different geometries studied in electrostatics and how the shape of a charged object affects the symmetry of the electric field, the potential difference between charged surfaces, and capacitance.

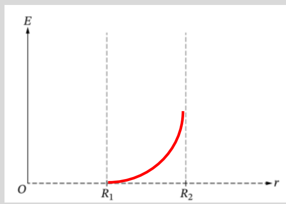
What common student misconceptions or gaps in knowledge were seen in the responses to this question?

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• An area integral has no significance on integration for the electric flux. The following was a common incorrect response: $$\int dA = \int 2\pi dr$$ This response indicates a misunderstanding of the application of a Gaussian surface and which quantity is meant to be summed. • The area of a Gaussian surface is synonymous with a cross-sectional area and/or the geometry of a Gaussian surface does not need to match the geometry of the charged object enclosed by the surface, as seen by following incorrect substitutions: $$\oint dA = \pi r^2$$ $$\oint dA = 4\pi r^2$$ • The radius of the Gaussian surface does not matter for the region $R_1 < r < R_2$. $$\oint dA = 2\pi R_1 \ell$$	• The closed surface area integral in Gauss's law indicates that the electric flux through all the infinitesimally small area elements dA through which electric field lines are directed must be summed. The geometry of an appropriate Gaussian surface for the level of calculus required for this course is one that matches the symmetry of the charged object enclosed by the surface. This closed surface is one in which the electric field lines are either parallel or perpendicular to area elements dA. A Gaussian surface symmetric to the geometry of the inner shell is required. While a Gaussian surface is a closed surface, the electric field is perpendicular to only the rounded part of the cylinder. Therefore, the surface areas of the caps are not included because there are not any electric field lines passing through them. $$\oint \vec{E} \cdot d\vec{A} = E(2\pi r \ell)$$
• Charge as well as linear, area, and volume density have the same meaning. $q_{\text{enc}} = \sigma_1$ $\rho = \frac{q_{\text{enc}}}{V}$ $q_{\text{enc}} = \rho V$	• Area charge density is defined as the charge that occupies a specified area of space divided by the surface area (not volume or length). $\sigma = \frac{q_{\text{enc}}}{A}$ $q_{\text{enc}} = \sigma A$

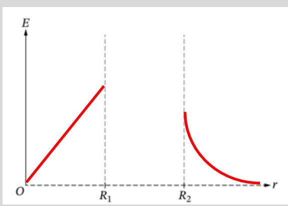
• The charge enclosed by the Gaussian surface occupies a region that extends to the radius of the Gaussian surface. $q_{\text{enc}} = \sigma_1 A$ $q_{\text{enc}} = \sigma_1 (2\pi r \ell)$	• The charge is located at a distance R_1 from the axis through the center of both shells. Therefore, the radius for the correct surface area is R_1. $q_{\text{enc}} = \sigma_1 A$ $q_{\text{enc}} = \sigma_1 (2\pi R_1 \ell)$
• The electric field in the region $R_1 < r < R_2$ is constant. • The electric field and the electric potential difference can be derived by summing an infinite sum of pieces of charge dq. $E = k\int \frac{dq}{r^2}$ $\Delta V = k\int \frac{dq}{r}$ While it is possible to solve for both the electric field and the electric potential difference beginning with these expressions, the calculus required to model cylindrical symmetry is beyond the scope of the course. These responses indicated that spherical symmetry was assumed.	• Gauss's law should be applied with the cylindrical symmetry of the charge distribution. A cylinder is used for both the surface area of the Gaussian surface and the charge enclosed by it. $\oint E \cdot dA = \frac{q_{\text{enc}}}{\varepsilon_0}$ $E(2\pi r \ell) = \frac{\sigma_1 (2\pi R_1 \ell)}{\varepsilon_0}$ $E = \frac{\sigma_1 R_1}{\varepsilon_0 r}$ The potential difference between R_1 and R_2 is related to the electric field within that region. $\Delta V = \int E dr$ $\lvert \Delta V \rvert = \int_{R_1}^{R_2} \frac{\sigma_1 R_1}{\varepsilon_0 r} dr = \frac{\sigma_1 R_1}{\varepsilon_0} \ln\left(\frac{R_2}{R_1}\right)$

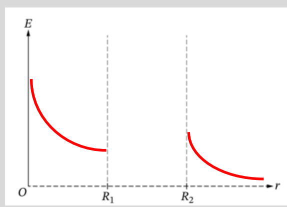
- Sketches for the graphs often did not match the derived expression for the region $R_1 < r < R_2$. The sketches also did not match the total charge enclosed for regions $r < R_1$ and $r > R_2$.
- Examples of incorrect sketches, even with the correct derived expression for the electric field E as a function of r, include the following for region $R_1 < r < R_2$:



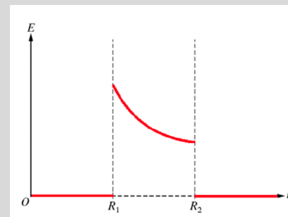


and for the regions $r < R_1$ and $r > R_2$:





- Because the correct expression for the electric field strength E for cylindrical symmetry indicates $E \propto 1/r$, the sketch of the graph for $R_1 < r < R_2$ should be an inverse curve.
- There is no charge for the region $r < R_1$, and the total charge enclosed by the Gaussian surface for $r > R_2$ is also zero.



- The expression for the parallel plate-capacitance, $C = \frac{\kappa \varepsilon_o A}{d}$, can be applied to capacitors of any geometry. The most common mistake in all parts of this question was the use of the parallel plate capacitance equation with a variety of substitutions for A and d.

$$C = \frac{\kappa \varepsilon_o A}{d} == \frac{\kappa \varepsilon_o \left(2\pi R_2 L - 2\pi R_1 L\right)}{R_2 - R_1}$$

- The correct response should relate capacitance to the charge stored on the plates of the capacitor and the potential difference between the plates.

$$C = \frac{Q}{\Delta V}$$

- Using the expressions derived in part A, the capacitance without a dielectric can be derived:

$$C = \frac{Q}{\Delta V} = \frac{\sigma_1 \left(2\pi R_1 L\right)}{\frac{\sigma_1 R_1}{\varepsilon_o} \ln\left(\frac{R_2}{R_1}\right)} = \frac{2\pi L \varepsilon_o}{\ln\left(\frac{R_2}{R_1}\right)}$$

- Adding a dielectric multiplies this expression by κ:

$$C = \frac{2\pi L \kappa \varepsilon_o}{\ln\left(\frac{R_2}{R_1}\right)}$$

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?

- Inform students that they should utilize an equation from the reference sheet and not to simply state memorized equations when asked to "derive" an expression.
    - Encourage students to reference the equations on the reference sheet throughout the course so that they have familiarity with their location.
    - Include the limits of integration, not arbitrary values (e.g., *a* and *b*).
    - Encourage students to show the steps for each action performed. Specifically, not to integrate and make substitutions of the limits of integration in the same step. Instead, encourage students to perform the integration and then substitute the limits of integration.
    - Instruct students to put one line through variables that cancel when found in every term of an equation. The variables should still be legible underneath the cancellation.
    - There is often a point earned for the substitution of a previous quantity into the correct expression even if that quantity was calculated incorrectly.
- When introducing Gauss's law, emphasize the difference between the integration in the table on the reference sheet versus the surface area integral in Gauss's law. Emphasize that integration is an infinite summation of a specified quantity and try to focus on the conceptual meaning of integrals, including the quantity being summed.
    - A Gaussian surface is an abstract tool for an abstract concept. Obtain as many visuals as possible, including animations of the electric field produced by the three geometries (planes, spheres, and cylinders).
    - Encourage students to draw two-dimensional and three-dimensional pictures of the charge distribution and the Gaussian surface for each derivation.
    - Direct students to the integration table on the reference sheet. Offer frequent reminders.
    - Set aside class time for students to practice and repeat this process on their own.
    - Post solutions in a shared electronic space for students to access. If possible, generate instructional videos for students to reference.
- Emphasize the three different geometries that students are expected to know for Gauss's law: planar, spherical, and cylindrical.
    - Introduce the derivation for each shape and offer multiple opportunities for students to practice each geometry.
    - Relate electric fields to gravitational fields to develop intuition. When studying motion at the surface of Earth, the gravitational field is essentially the same symmetry as one produced by a "flat" Earth—that is, planar symmetry. But when studying orbital motion, the gravitational field is derived using spherical symmetry. Indicate how this corresponds to planar and spherical symmetry in the context of charge distributions.
    - Find creative ways for students to practice the derivations. For the cylindrical geometry in this particular question, a break in practicing the derivation may include the following video of water droplets orbiting a charged, cylindrical knitting needle: https://www.youtube.com/watch?v=qHrBhgwq__Q. The difference in the expressions for the orbital period of planets versus the orbital period of the water droplets in the video referenced above is also interesting to highlight. Because the spherical gravitational field is proportional to $1/r^2$, Kepler's third law relates planetary orbital period, *T,* to orbital radius, *r,* according to $T^2 \propto r^3$. With the cylindrical geometry of the water droplets, the field is proportional to $1/r$, which means that the period of the orbiting water drops is independent of the distance from an infinitely long cylindrical distribution.

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 units 8 and 9 progress checks and AP Daily videos on electric fields, forces, and potential.
- Teachers should assign topic questions (Topics 8.4, 8.5, 8.6, and 9.2) to monitor progress being made in the mastery of content.

Question 2

Task: Translation Between Representations
Topic: Electromagnetic Induction

	Max Points:	Mean Score:
A1	1	0.96
A2	1	0.76
A3	1	0.60
B1	1	0.74
B2	1	0.69
B3	1	0.62
B4	1	0.42
C1	1	0.57
C2	1	0.58
C3	1	0.62
D1	1	0.76
D2	1	0.43

Overall Mean Score: 7.76/12

What were the responses to this question expected to demonstrate?

The responses were expected to:

- Represent, in a bar chart, the absolute value of electromotive force (emf) induced in a circular conducting loop rotating in a uniform external magnetic field at specific times during the loop's rotation
- Identify points in time where the induced emf is zero due to the orientation of the loop within the uniform magnetic field and nonzero values of the induced emf, relative to the value given in the bar chart, at specific times during the rotation of the loop
- Derive an expression for the maximum current induced in the rotating loop using Faraday's law of induction and Ohm's law
- Determine the emf induced in the loop by differentiating the given expression for magnetic flux
- Identify the maximum induced current at particular points of rotation
- Graphically represent the instantaneous power dissipated by the loop as a function of time
- Compare the graphical representation of power as a function of time to the bar chart representation of induced emf as a function of time
- Justify the comparison between the two representations by discussing the functional dependence between the power dissipated by the loop and the emf induced in the loop

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?

- Almost all responses correctly identified a nonzero induced emf at the correct time with more than three quarters indicating the absolute value of the nonzero magnetic force is the same as the given value. Some responses indicated the induced emf to be much lower than the given value.
- Most responses correctly identified zero induced emf at time zero, but many responses did not indicate the second time where the induced emf was zero.
- Around three quarters of the responses included an expression representing Faraday's law in a multistep derivation. However, some responses listed several unrelated expressions that appear in the reference material.
- Most responses correctly found the derivative of the given expression for flux and identified this as induced emf.

- Many responses did not then use Ohm's law to find the induced current with only around 60% earning this point and fewer than half correctly identifying the maximum current. Many responses instead left the expression as a function of time.
- Approximately 60% of the responses showed an approximate sinusoidal shape featuring a noticeable change in concavity while a significant number showed no points of inflection or were linear.
- Most responses featured a graph with exactly two cycles while incorrect responses typically showed only one or did not show any cyclical behavior at all.
- Many responses started at the origin, increased to a maximum value at least once, and returned to the horizontal axis representing zero power dissipated by the loop. However, some responses were inverted starting at a nonzero value for power.
- More than three quarters of the responses correctly indicated that their bar chart representation was consistent with their graphical representation. However, fewer than half of the responses correctly justified the consistency of the representations by correctly relating power with emf squared. Many responses incorrectly related power with emf indicating a linear relationship.

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 induced emf increases linearly with time as the loop rotates within the magnetic field with no cyclical behavior.	• Induced emf depends on the instantaneous rate of change of magnetic flux through the area enclosed by the loop. During one complete revolution, this rate of change will start at zero and reach the same maximum twice and reach zero two more times.
	    ○ A bar drawn in the $T/4$ column with a height of 3 units
	    ○ A zero written in the $t = 0$ and $T/2$ columns (Note: A horizontal line of a height of 0 units was also acceptable.)

The following were observed in the derivation using Faraday's law: • Including an incorrect expression that cannot be used to derive maximum induced current • Not differentiating between electromagnetic force and current • Deriving an expression for induced current as a function of time instead of the maximum induced current • Indicating the final derived expression for maximum induced current without showing a multistep derivation	• Use the correct expression of Faraday's law, substitute the given expression for magnetic flux, and find the derivative as a function of time. Identify the maximum value of $\sin(\omega t)$ as 1. $\varepsilon = -\frac{d\Phi_B}{dt}$ $\varepsilon = -\frac{d}{dt}\left(BA\cos(\omega t)\right) = BA\omega\sin(\omega t)$ $I = \frac{\Delta V}{R} = \frac{\varepsilon}{R} = \frac{BA\omega\sin(\omega t)}{R}$ $\sin(\omega t)$ has a maximum value of 1, so the maximum value of I is $BA\omega/R$.

• Not drawing an approximately sinusoidal curve	• Draw a sinusoidal curve that has exactly two complete cycles, starts at the origin, and has equal maximum and minimum values.
• Demonstrating an incorrect translation between their two different representations of data • Indicating power to be directly related to emf and not taking into account the time dependence of current	• The sketch in part C is consistent with the bars drawn in drawn in part A. Power P is proportional to ε^2, so the zeroes in the sketch are consistent with the zero columns at $t = 0$ and $t = T/2$, and the equal powers at $t = T/4$ and $t = 3T/4$ are consistent with the equal bar heights at those two times.

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?

- Plan the school year such that sufficient time can be spent studying electromagnetic induction. Be sure that the students work through several mathematical and conceptual problems, including the AP Classroom progress checks.
- Demonstrate different scenarios that will cause emf to be induced and have the students draw graphs for magnetic flux, the change of magnetic flux, and the induced emf for each scenario.
- Use calculus to demonstrate the relationship between each curve mentioned above and have students practice finding derivatives and writing definite integrals.
- Compare the difference between changing magnetic flux and induced magnetic field as it relates to Lenz's law.
- Assign practice derivations starting from first principles or fundamental equations on the equation sheet. Avoid allowing students to utilize shortcuts that, while seemingly convenient, do not allow them to effectively communicate their derivation skills.
- Assign multipart problems that ask students to translate information from two different representations and justify using the functional dependence between two variables. Score student work to give credit for consistency with prior work.
- Have students practice translating between representations throughout the entire course.
    - Provide one group of students with various representations (e.g., bar charts, graphs, or data tables). Provide a second set of students with other representations (e.g., bar charts, graphs, or tables) that contain data that will match only one of the representations given to the first set of students. The matching data sets will be represented in a different format and will be expressed in terms of different variables. Students can interact to find the correct representation of their data.
    - Find examples of translations between multiple representations by looking through AP Classroom FRQ-tagged Translation Between Representations (TBR) questions.
- Ensure that students understand the meaning of functional dependence.
    - Provide students with a fundamental equation and highlight two variables used in the equation.
    - Have students discuss the functional dependence between the given variables.
    - After students have completed their discussion, have them create a sample representation of data in a bar chart, graph, and data table. Each representation should have exactly one change to the data (e.g., a bar chart of ε vs. t paired with a graph of P vs. t).

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 Unit 13 progress checks and AP Daily videos on electromagnetic induction.
- Teachers should assign topic questions (Topics 13.2 and 13.3) to monitor progress being made in the mastery of content.

Question 3

Task: Experimental Design and Analysis
Topic: Resistance and Resistivity

	Max Points:	Mean Score:
A1	1	0.46
A2	1	0.83
B1	1	0.66
B2	1	0.55
C1	1	0.91
C2	1	0.78
C3	1	0.91
C4	1	0.83
D1	1	0.77
D2	1	0.68

Overall Mean Score: 7.37/10

What were the responses to this question expected to demonstrate?

The responses were expected to:

- Describe a procedure to collect data to calculate the resistivity of a circuit element with a specific length and cross-sectional area using a variable power supply and an ammeter
- Design a lab procedure in which multiple measurements are made to reduce experimental uncertainty
- Determine how to graph potential difference and current data to determine resistivity
- Identify the quantities to graph that show a linear relationship between resistance and length of a resistor to determine resistivity given data on the length, resistance, and cross-sectional area of cylindrical resistors
- Prepare a graph with appropriate scaling and axes with appropriate labels and units and plot data consistent with data table
- Draw a best-fit line using a straightedge that follows the trend of the plotted points
- Determine how resistivity is functionally related to the slope of the line
- Calculate a resistivity value from the slope

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 correctly stated a procedure that included recording at least one current and one length measurement.
- Many responses included a procedure that included a measurement of the radius or diameter of the circuit element but did not relate that measurement to the cross-sectional area.
- A significant number of responses showed confusion between the terms calculate and measure. For example, "use the ruler to calculate the length" or "use the ruler to measure the area."
- Some responses referenced the voltmeter and ammeter without specifying that measurements needed to be taken or what quantity the meter measures.
- Some responses attempted to vary both the electric potential difference and the length of circuit element in parts A and B.
- Nearly all responses correctly stated a procedure that included recording multiple data sets to reduce experimental uncertainty.
- Almost 70% of the responses correctly described how their collected data could be graphed to determine resistivity.
- Responses were generally very successful at graphing the data in part C with over 90% identifying what should be plotted and plotting the data.

- Nearly as many responses correctly scaled the axes and labeled them appropriately with names or symbols and units and were able to draw an appropriate line of best fit for the plotted data.
- Around three quarters of the responses correctly related their slope value to the corresponding expression to calculate a correct value for resistivity.

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 reading the prompt carefully. Some responses used an expression for surface area instead of cross-sectional area	• Responses measured the diameter of the cylindrical resistor and then calculated the cross-sectional area using $\pi\left(\frac{d}{2}\right)^2$.
• Indicating an incorrect placement of voltmeters and ammeters in the circuit	• Responses indicated the voltmeter is placed in parallel with the resistor to measure electric potential difference and the ammeter placed in series with the resistor to measure current.
• Not labeling axes with both the quantity and the units; for example, labeling an axis only "Resistance" or "ohms"	• Responses label the vertical axis as Resistance (Ω) and the horizontal axis as Length (m).
• Incorrect graph scaling. Responses showed the creation of graph scales based on specific data points rather than using equal increments.	• Responses indicated a scale that begins at zero and has values of 1, 2, 3, 4, and 5 Ohms labeled on the vertical axis and they are each equally spaced.
• Calculating the slope of a best-fit line based on only one data point and the origin. This would only produce a correct value if the best-fit line passes through the origin.	• Responses clearly indicated two points on the best-fit line and showed a calculation of the slope using these points.
• Not providing a relationship between the slope and the expression used to find the resistivity	• Responses indicate that $\text{slope} = \Delta\left(\frac{\Delta R}{\Delta L}\right) = \frac{\rho_2}{A}$.

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?

- Whenever possible, students should be exposed to hands-on lab experiences. This is especially important for students in an electricity and magnetism course where much of the material is somewhat abstract. Demonstrations can help when there is no other alternative.
- Conduct simple Ohm's law labs that require students to place both voltmeters and ammeters in the circuit correctly.
- Conduct labs using variable power supplies and a single resistor to calculate resistivity of the material by analyzing graphs.

- Conduct labs involving resistors made of the same cross-sectional material of various lengths to calculate resistivity of that material by analyzing graphs. Pencil lead, for example, can be used as such material.
- Have students practice scaling axes using data that has been given in scientific notation and practice calculating the slope of the resulting line.
- 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 exam room.
- Whenever students are using or drawing a graph, ask them to deduce the physical significance (if any) of its intercepts, slope, and area bound between the curve and the horizontal axis.
- Practice having students focus on using two points that are on the best-fit line and clearly show which points are being used to calculate the slope of the best-fit line. Have students show $\frac{y_2 - y_1}{x_2 - x_1}$ with values substituted when calculating slopes.

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

- Use Progress Check Lab FRQs in all units to practice experimental design and analysis skills.
- Teachers should direct students to Unit 11 progress checks and AP Daily videos on circuits.
- Teachers should assign topic questions (e.g., Topics 11.2, 11.3, and 11.5) to monitor progress being made in the mastery of content.

Question 4

Task: Qualitative/Quantitative Translation
Topic: Magnetic Field and Force Due to Current-Carrying Wire

	Max Points:	Mean Score:
A1	1	0.75
A2	1	0.56
A3	1	0.47
B1	1	0.73
B2	1	0.45
B3	1	0.58
C1	1	0.55
C2	1	0.48

Overall Mean Score: 4.57/8

What were the responses to this question expected to demonstrate?

The responses were expected to:

- Use the right-hand rule to determine the direction of the magnetic field produced by a long, straight, current-carrying wire
- Reason qualitatively about the relative magnitude of the magnetic field from a long, straight, current-carrying wire at two locations
- Add the magnetic fields produced by two long, straight current-carrying wires to find the magnitude of the total magnetic field at a location near those wires
- Use the information about the magnetic field at the location of a moving, charged sphere to reason about the magnitude of the magnetic force exerted on the sphere.
- Justify a claim about the relative size of the magnetic forces on two moving, charged spheres that references the magnetic fields at the location of the two spheres
- Select an appropriate fundamental equation to use in a derivation for the net magnetic field due to two long, straight, current-carrying wires
- Derive the expression for the magnetic field produced by a long, straight, current-carrying wire using Ampere's law
- Make and justify a claim about how the magnitude of a magnetic force from a long, straight, current-carrying wire will change if the magnitude and direction of the current in the wire is changed

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 correctly applied the right-hand rule to determine the direction of the magnetic field from a long, straight, current-carrying wire in the regions around the wire.
- Approximately three quarters of the responses correctly indicated that the magnitude of the net magnetic field is larger when parallel fields are added together and is smaller when anti-parallel fields are added together.
- Most responses correctly argued that the magnitude of the net magnetic force on a moving charge is proportional to the magnitude of the net magnetic field at the location of that charge, either qualitatively or by referencing $F_B = qvB$.
- Few responses discussed that the charges and velocity of two moving spheres are equal when justifying a claim about the relative magnitudes of the magnetic forces on those spheres.

- Some responses attempted to justify the claim that the magnetic forces applied by two current-carrying wires on a moving charged sphere were in opposite directions without referencing the direction of the magnetic fields produced by those wires.
- Most responses (around three quarters) chose an approach that could successfully be used to derive the magnetic field from a long, straight, current-carrying wire. However, some responses used the Biot-Savart law as the basis for their derivation, which is a much more difficult approach than using Ampere's law. Very few of the derivations that began with the Bio-Savart law were successful. Roughly half of students successfully derived an expression for the magnetic field of a long, straight current-carrying wire.
- Most students correctly indicated that the net magnetic field at a position halfway between two long, straight current-carrying wires with currents of equal magnitude and opposite directions was twice the magnitude of the field from one of those wires.
- Around half the responses made and justified a correct claim about how the magnitude of the net magnetic force from a pair long, straight, current-carrying wires on a moving charged sphere would change if the magnitude and direction of the current in one of the wires is changed.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Incorrectly using the equation $F = \int I d\vec{\ell} \times \vec{B}$ to relate the magnetic field at the location of a charged sphere to the magnetic force applied to the charged sphere	• Successful responses correctly used the expression $F_B = qvB$ to relate the magnetic field at the location of a charged sphere to the magnetic force applied to the charged sphere. Using the equation $F_B = qvB$, a response can demonstrate that if q and v are the same, a greater magnitude of magnetic field means that there will be a greater force
• Claiming that the direction determined by applying the right-hand rule to a long, straight current-carrying wire was the direction of the magnetic force applied by that wire on moving, charged sphere	• Successful responses used the right-hand rule to find the direction of the magnetic field from the long, straight current-carrying wire. The magnetic fields from wires S and T both point into the page at the location of Sphere 2. However, the magnetic fields from wires S and T point in opposite directions at the location of Sphere 1.
• Not indicating that the velocities and charges of two spheres were equal in justifications for why one sphere experienced a larger magnitude of magnetic force than the other • Not including the different distances from Wire T to each sphere in their justifications • Not including relative directions of the magnetic fields by the two wires at the location of the spheres and only discussed the relative directions of the magnetic forces applied by the two wires	• Successful responses included each component of a full justification: The magnetic fields from Wire S and Wire T point in the same direction at the location of Sphere 2, and in opposite directions at the location of Sphere 1. In addition, Sphere 1 is a distance $3d$ from wire T, while Sphere 2 is only a distance d from Wire T. These statements both contribute to B_2 being larger than B_1. Because the charges and velocities of the two spheres are the same, the larger magnitude of the magnetic field at Sphere 2 means there will be a larger magnitude of magnetic force on Sphere 2.

• Incorrectly substituting an enclosed current $I_{\text{enc}} = 2I$ into Ampere's law in a derivation for the net magnetic field produced by two long, straight, current-carrying wires • Incorrectly substituting the circumference of an Amperian loop of radius d	• Successful responses correctly substituted $\ell = 2\pi d$ and $I_{\text{enc}} = I$ into Ampere's law to find the magnetic field from a single wire of current I , a distance d away from Sphere 2. Then they summed the fields from wires S and T to find the net field.
• Indicating that the net magnetic field due to two current carrying wires could be found from the sum of the current in the two wires: In the original scenarios $I = -I - I = -2I$ and $B = \dfrac{\mu_0(-2I)}{2\pi d}$. Now the current in Wire T is $3I$, so the net current is $I = (3I - I) - 2I$. Because the magnitude of the net current is the same, the magnitude of the magnetic field will be the same.	• Successful responses clearly stated that when the magnitude and direction of the current in Wire T changes, the magnitude and direction of the magnetic field due to Wire T changes. Because Wire T now has current $3I$, B_T is three times bigger. However, the direction of the current also changed, so now the two fields point in opposite directions, so $B_{tot} = \dfrac{3\mu_0 I}{2\pi d} - \dfrac{\mu_0 I}{2\pi d} = \dfrac{\mu_0 I}{\pi d}$. Because the magnitude of the magnetic field strength is unchanged, the magnitude of the force on the sphere is unchanged.

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?

- Assess students using the *justify* task verb as it's defined in the *AP Physics C: Electricity and Magnetism Course and Exam Description*. It can be useful to have students review each other's justifications for clarity and logical completeness.
- Have students practice working with equations to identify variables and describe how changes in a variable will lead to changes in a derived quantity. Emphasize that this prediction can only be made if one assumes that all other variables are constant. Have students apply this type of reasoning to a scenario where they need to identify how variables will change and why.
- Stress that when making written arguments in physics, it is necessary to use precise terminology (e.g., "net magnetic field" instead of "field"), either with words or symbols. Students should have extensive practice with mathematical symbols and scientific terminology. Be sure to use precise terminology when speaking about physics to students.
- Make sure that students understand that finding the direction of the magnetic force on a moving charged object from a current-carrying wire requires the use of a right-hand rule twice. It is first needed to find the direction of the magnetic field due to the current and second to find the direction of the force using the directions of the magnetic field and the velocity of the object.
- Familiarize students with the geometries that allow for easy use of Ampere's law to find an expression for magnetic field strength and emphasize that it is much easier to apply Ampere's law in these situations than the Biot-Savart law.

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 Unit 12 progress checks and AP Daily videos on magnetism.
- Teachers should assign topic questions (e.g., Topics 12.2 and 12.4) to monitor progress being made in the mastery of content.