AP® CollegeBoard

Chief Reader Report on Student Responses:

2021 AP® Physics C: Electricity and Magnetism Free-Response Questions

• Number of Students Scored	20,471		
• Number of Readers	461 (for all Physics exams)		
• Score Distribution	Exam Score	N	%At
	5	6,666	32.6
	4	4,735	23.1
	3	2,826	13.8
	2	3,683	18.0
	1	2,561	12.5
• Global Mean	3.45		

The following comments on the 2021 free-response questions for AP® Physics C: Electricity and Magnetism were written by the Chief Reader, Shannon Willoughby, Montana State University. 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:** Determine potential difference, charge, and current in an RC circuit **Topic :** Resistor/capacitor circuit

Max. Points: 15 **Mean Score:** 6.42

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Identify a short in a circuit.
- Recognize that the steady-state current is zero in branches with fully-charged capacitors.
- Determine the potential difference across charged capacitors, wired in series and/or in parallel.
- Determine the potential difference across a resistor with charge flowing through it and across resistors wired in series and/or in parallel.
- Identify equipotentials in a circuit.
- Analyze how changes in the overall capacitance affect the time it takes for capacitors to discharge and to model these changes graphically.
- Relate the charge stored on a capacitor to its capacitance and the potential difference across it.
- Relate the current in a resistor to its resistance and the potential difference across it.

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?

- An overall weakness is in correctly applying potential difference across different points in the circuit.
- It was evident that many students were simply memorizing equations or using them from the equation sheet without considering their meaning or the function of a resistor and/or capacitor.
- Poor use of ratios without identifying the physics behind these ratios was common, such as using ratios of arbitrary quantities without being explicit about the physics motivating the use of the ratio.
- Students frequently did not demonstrate that they were thinking about the flow of charge when completing calculations, for instance, whether a capacitor is charged, and why the current eventually stops when a capacitor is fully charged.

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 potential difference across the battery is the potential difference across every device in the circuit.	• The student is able to correctly identify that the potential difference across R_2, R_3, C_{12}, and C_3 is the same. • The student is able to correctly identify that the potential difference across C_1 and C_2 is equal to the potential difference across R_2, which is equal to the potential difference across R_3. • The student is able to calculate the potential difference across R_1 when the capacitors are fully charged.

• Changing the overall capacitance in the discharge circuit, lowered the potential difference across the R_2, R_3, C_{12}, and/or C_3.	• The student is able to recognize that the potential difference across the capacitors is determined by current flow through the resistors. Decreasing the overall capacitance of the circuit reduces the time it takes for the capacitors to discharge.

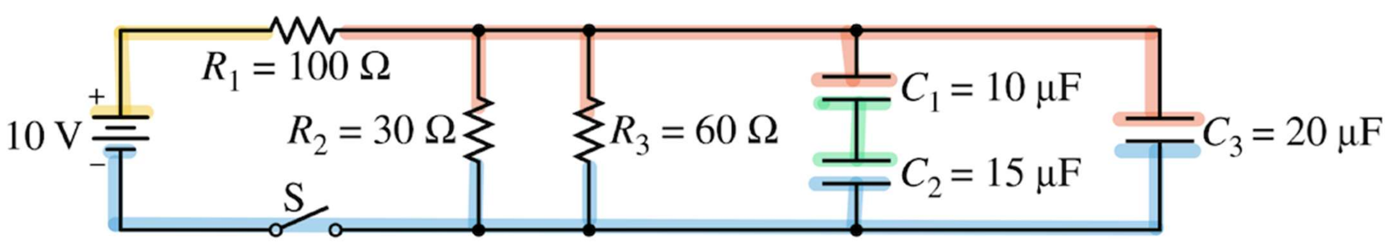
Based on your experience at the AP® Reading with student responses, what advice would you offer teachers to help them improve the student performance on the exam?

Students should be taught to think about the movement of charge when the switch in a circuit with a battery and capacitors is first closed, either by discussing the actual electron movement or the movement of positive charge carriers. Teachers can emphasize that at $t = 0$, when the switch is first closed, there is no charge on the capacitor plates, so there is nothing to inhibit the movement of charge (again, either electrons or positive charge carriers). This is why at $t = 0$, the capacitors behave as wires, shorting R_2 and R_3.

Students should be encouraged to label the capacitor plates in a circuit diagram with a positive (+) or negative (–) sign, indicating the charge on the plate for clarity.

It is valuable to spend a lot of time developing the concept of potential. Analogies to height are helpful. For instance, using spandex to discuss the warping of space with gravity fields and electric fields can provide a visual representation in which a mass (or a negative charge) will cause the spandex to bend downwards, causing an attraction with any other test mass (or test charge), and a positive charge will cause the spandex to bend upwards causing repulsion with another test charge. (For instance, see https://www.youtube.com/watch?v=MTY1Kje0yLg.)

Students should be encouraged to identify equipotentials in a circuit, for instance, by teaching students to color parts of the circuit that are at the same potential. For example, a long time after the switch is closed, there is an electric field between the capacitor plates, and therefore a potential difference across the plates ($\Delta V = -Ed$). Remind students that potential is constant in the branches where there is a current flowing because we assume that we are dealing with wires of negligible resistance and that potential is constant in the branches with capacitors because there is no current when the capacitors are fully charged. With equipotentials noted, it is easy to see that the potential difference across R_2, R_3, C_{12}, and C_3 is the same. It also is easy to see that there is potential difference across R_1.



It is worth reminding students (repeatedly) that ΔV = energy/charge and that potential always decreases in the direction of electric field vectors. Ask students to draw the electric field lines between capacitor plates. Remind students that there is an electric field in the branches of the circuit that have a current. The electric field points in the same direction as the electric force on positive charge carriers (i.e., in the direction of current flow). Encourage students to label the higher and lower potential on either side of the resistors. Remind students that resistors convert electrical energy into another form of energy (generating thermal energy) and that capacitors store electrical energy. Hence, there is a potential difference across each resistor (charge moves through it) as well as each capacitor (as charge builds on the plates).

Question #2 **Task:** Calculate the charges on conducting spheres based on experimental data **Topic:** Electrostatics

Max. Points: 15 **Mean Score:** 6.93

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Construct an appropriate best-fit line for experimental data provided in graphical form.
- Utilize math skills to calculate a slope, interpret a graph containing inverse quantities, and correctly use the units given for experimental data to calculate an unknown quantity.
- Relate the slope of a linearized graph to appropriate physical quantities.
- Relate a mathematical representation (e.g., best fit line's vertical intercept) to a physical quantity stemming from the experimental design.
- Recognize how nonideal experimental behavior that occurs in a laboratory setting and is manifested in graphs of experimental data.
- Analyze experimental evidence to see if it is consistent with a proposed claim.
- Construct and justify a physical representation of the location of excess charge in polarized conductors that is consistent with a proposed claim.
- Use Coulomb's Law to relate electric force to distance between charges and magnitude of charges.
- Recognize net force as a vector sum of gravitational and electric forces.
- Demonstrate an understanding of the vector nature (attraction or repulsion) of electric charge interactions.
- Understand the resulting location of excess charge in polarized objects.

How well did the responses address the course content related to this question? How well did the responses integrate the skills required on this question?

- The majority of students successfully recognized the need for a straight-line fit of the data in part (a). However, far fewer were able to properly calculate the slope because they did not read the units of the vertical axis properly or recognize the graph had a nonzero vertical intercept. About half of the students properly used Coulomb's Law to relate the slope of the graph to the excess charge on each sphere and fewer correctly calculated the charge. Interpreting a graph of an inverse quantity was also a weakness for many students. Most students recognized which data point represented the closest distance between the spheres, but many students were unable to correctly calculate the distance of the closest approach from the given value. A significant minority also incorrectly chose to substitute the data point into Coulomb's Law to calculate a predicted distance between the spheres rather than find the distance that was measured in the experiment. Over half of the students were not able to identify the vertical intercept as the weight of the lower sphere and rod, with many students writing purely mathematical responses that were equivalent to "the y-intercept is the y-value when x is zero." Students who recognized that the electronic balance was measuring the sum of two forces (gravitational and electric) did very well on the end of part (a) and in the justification in part (d), but these students were in the minority.
- About half of the students misinterpreted the prompt in part (b), which asked whether the observed data could be caused by charge leaking over time. Likely due to a lack of experimental experience, some of these students incorrectly assumed that part (b) was asking them to assess whether or not charge could indeed leak from a sphere held by an insulating string, while others gave various physical justifications of how charge could leak away rather than answering the question asked.
- In part (c), where students were asked to draw the location of the excess positive charge on the polarized spheres, roughly three-quarters of students were unable to do so correctly. Few were able to link the increased distance between the excess charges to the reduced electric force.

- A large majority of students recognized that the excess negative and positive charges would be attracted to each other (part d), drawing the symbols for the excess charges in the correct locations. Most students appeared to have misinterpreted the prompt for (d)(ii) as asking about the magnitude of the resulting electric force rather than the magnitude of the force reading on the electronic balance. Referring only to the electric force, some answered "equal to" because the magnitude of the charges did not change or "greater than," arguing that the spheres would polarize to reduce the distance between the excess charges. The intent of the question was to test the students' understanding of the vector nature of the electric and gravitational forces because an attractive electric force would lower the force reading. A small percentage of the students were successful in this regard.

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 slope of the graph is Q, the charge of one sphere (the unknown physical quantity).	• Used Coulomb's Law, the slope of the F vs. $(1/d^2)$ graph is kQ^2.
• Used data points that are not on the line to calculate the slope.	• Used points on the best-fit line to calculate the slope. • Did not use (0,0) in the slope calculation.
• Assumed that the vertical axis values are in base SI units (Newtons).	• Correctly accounted for the metric prefix (force given in micro Newtons) when calculating slope values.
• In a graph with $1/d^2$ on the horizontal axis, calculated the slope using inverses of the abscissa values.	• Calculated the slope using the given values from the horizontal axis.
• In part a(v) about the vertical intercept, stated that when $x = 0$, d is also zero, so the spheres are touching or are very near each other. (Students were unable to properly interpret an inverse graph in which $1/d^2$ was plotted on the horizontal axis.)	• The vertical intercept occurs when $x = 0$ or $1/d^2 = 0$, which means either that d is infinite or that the spheres are very far from each other.
• The vertical intercept is the mass of the sphere and rod.	• The vertical intercept is the weight (or gravitational force) of the sphere and rod.
• The vertical intercept is the "starting force" or "initial force." • Assumed that the vertical or horizontal intercept is zero or not related to an experimental quantity or attribute. • Used purely mathematical language rather than refer to the physical situation or the experimental setup.	• Because the electronic balance measures the weight plus the electric force, when $1/d^2 = 0$ and the spheres are very far apart, the electric force is negligible, and the vertical intercept is only the weight of the lower sphere and rod. OR • Because the balance is zeroed after the lower sphere and rod are placed on it but before the upper sphere is introduced, the

	weight is the only force being measured by the balance at the beginning of the experiment.
• The vertical intercept is the "force between the spheres when they are infinitely far apart."	• When the spheres are infinitely far apart, the electric force between them is negligible. The only remaining force measured by the electronic balance is the weight of the lower sphere and rod.
• Charge can't leak from the sphere because the string is insulating. • *Note: The question did not ask about the mechanism for the charge leak; rather it asked if a charge leak was a possible reason for the observed data.*	• Reading the question carefully and understanding that the prompt asked whether or not a charge leak could lead to the given graph of experimental results. • A good response to the prompt: Because the electric force is proportional to the product of the charges, if one of the charges decreased in magnitude, it would lead to the observed decrease in the measured electric force for the later data points. • Important background knowledge: Recognizing that real-life experiments are often non-ideal. Charge CAN leak through an insulating string or to the surrounding air.
• In part (c) the sides of the spheres that did not have "+" signs were negatively charged, leading to an attractive force between the spheres, reducing the force.	• Once the spheres were polarized, the distance between the excess positive charge on each was larger than the distance between the centers of the spheres. A larger distance in Coulomb's Law leads to a smaller repulsive force.
• *Note: Part (d) didn't ask about the magnitude of the electric force between the spheres, it asked about the magnitude of the force reading (on the electronic balance). The response below is not a physics misconception. It was a misreading of the prompt.* A typical response from a student who incorrectly checked "Equal to:" In part (d) when the spheres have opposite charges, the spheres now attract each other, but the electric force is equal in magnitude to the electric force when they were both positively charged; the magnitude of the electric force in Coulomb's Law depends only on the magnitude of the charges, which remained the same as in part (c).	• Now that the spheres are oppositely charged, they attract each other. Therefore the electric force pulls upward, opposing the gravitational force (or partially lifting the lower sphere off the balance), reducing the force reading on the electronic balance.

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 involving a best-fit line, make students practice drawing their lines with a ruler or straight edge.
    - Tip: Pair up students to critique each other's lines. Should it be steeper or less steep? Are there points both above and below the line? Should the line be shifted? Should the line go through the origin or not?
    - Tip: Assure that students always use pencils when drawing graphs. Erasures need to be fully erased. On digitally scanned student responses, readers cannot tell the difference between pen and pencil lines or different colors.
- When they are calculating a slope from a best-fit line, have students mark the two points on the line or write ordered pairs for the two points they will use in their calculation AND show the subtractions in the numerator and denominator of their slope calculation.
- Ask students to habitually check units on all given quantities and on both axes of a graph to see if non-standard units or metric prefixes are being used or if conversions are needed. Units should be provided on all final numerical answers.
- When assigning linearization problems or labs that require the linearization of a graph, choose some that have a nonzero horizontal or vertical intercept and model how to identify the physical quantity associated with the intercept.
- Assign problems where an inverse ($1/x$ or $1/x^2$) is on at least one axis to give students experience with such graphs.
- When discussing polarization, include examples where the polarized objects have a net positive or negative charge as well as those when the objects are neutral.
- Encourage the use of free-body diagrams to analyze situations where forces are involved.
- Always include a discussion of non-ideal lab behavior or sources of error and their effect on measured quantities in lab assignments and lab-based FRQs.
- When they are justifying answers, require students to address the physics of the specific situation, rather than simply the mathematics. They should not simply restate the checkbox or the information in the prompt as a justification.
- At least two parts of this question were consistently misread or misunderstood by students. In addition, some students did not follow clear instructions like "draw a single '+' sign," etc. It is important to follow the directions in the prompt.
    - Tip: When doing a problem in class, ask students to practice reading and then restating the question (in writing or to each other).
    - Tip: When students are checking their work, they should ask themselves, "did I answer the question that was asked?"

Question #3 **Task:** Determine current, energy dissipated, and emf for coil with changing magnetic field **Topic:** Electromagnetic Induction

Max. Points: 15 **Mean Score:** 4.08

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate understanding of:

- The concept of induced emf.
- How to calculate magnetic flux when the magnetic field is time dependent.
- How to calculate energy when power is time dependent.
- How the magnetic flux is affected by a change in relevant variables.
- The relationship among frequency, period, and amplitude for a physical quantity with a sinusoidal time dependence and their graphical representations.

The responses were expected to demonstrate the ability to:

- Support a claim with a correct and complete explanation based on clear physical reasoning.
- Perform calculations involving calculus to provide correct numerical answers with correct units.
- Understand the relationship between parameters in an equation and characteristics of a graph.
- Deduce the effect of changing a variable on the behavior of a physical system.

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?

Students demonstrated a broad range of mastery of the concepts related to electromagnetic induction and electrical power/energy, as well as of the relevant mathematical and argumentation skills.

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 the meaning of a derivative and incorrectly writing emf = $(BA)/t$	• emf = $d\Phi/dt = A\,dB/dt = A\beta/t^2$
• Not understanding how to calculate E from $P(t)$ and writing $E = Pt = P(t_1)t_1 - P(t_2)t_2$ or similar	• $E = \int_{t_1}^{t_2} P\,dt = \int_{t_1}^{t_2} I^2 R\,dt$ and substituting I with an expression as a function of t
• Inability to derive an expression for the emf as a function of time in order to determine its maximum and connect the result with the sketch of a graph	• emf = $d\Phi/dt = d(B_0 A \cos\omega t)/dt = B_0 A\omega \sin\omega t$, so $\text{emf}_{MAX} = B_0 A\omega$; therefore, doubling the ω doubles the amplitude in the graph emf(t)