Chief Reader Report on Student Responses:

2022 AP® Physics 2 Free-Response Questions

• Number of Students Scored	17,842		
• Number of Readers	471 (for all Physics exams)		
• Score Distribution	Exam Score	N	%At
	5	2,909	16.3
	4	3,222	18.1
	3	6,301	35.3
	2	4,293	24.1
	1	1,117	6.3
• Global Mean	3.14		

The following comments on the 2022 free-response questions for AP® Physics 2 were written by the Chief Reader, Brian Utter, Teaching Professor, 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: Paragraph-Length Response
Topic: Optics and Fluids
Max Score: 10
Mean Score: 5.32

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Apply Newton's laws to a situation involving buoyancy.
- Relate the index of refraction of a medium, the speed of light in the medium, and the wavelength of the light in the medium.
- Demonstrate that when light travels from one medium to another, the frequency of the light does not change.
- Describe the relationship between the wavelength of light and the interference pattern it produces when going through a double slit.
- Use Snell's law at an interface between two optical media, including the meaning of the normal line.
- Create a free-body diagram.
- Perform a mathematical derivation.
- Write a coherent paragraph presenting a scientific analysis of a situation.

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 were presented with sufficient clarity that a student's thought process could be followed. The vast majority of responses attempted to apply appropriate physics concepts. The most notable exception to this was that a significant number of responses incorrectly applied Snell's law in the paragraph about physical optics in part (b).
- Most responses indicated an understanding of Newton's laws and identified the appropriate forces to include on the diagram drawn in order for a solution to be started.
- A nonnegligible number of students did not begin a derivation from an explicit statement of Newton's second law as the general principle. The most common error on part (a) of the free-response question was using the density of the block, rather than that of the displaced fluid, when writing an expression for the buoyant force exerted on the block.
- Most responses for part (b) discussed frequency, wavelength, and wave speed. Even when responses exhibited misunderstandings of how these characteristics are affected when a wave propagates into a new medium, there were usually one to two correct statements in the paragraph.
- Fewer responses addressed the relationship between wavelength and the interference pattern, and some responses indicated a misunderstanding of what the quantities in that relationship stood for.
- Most responses in part (c) indicated an awareness that Snell's law was relevant to the situation but often did not clearly explain how the law applies to the situation. The most common reason for not earning the first point of this part was for not indicating that the prism's index of refraction played a role in the analysis of the situation. There were also responses that indicated a lack of understanding about the position of the normal line and/or how the angles of incidence and refraction are measured.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• When calculating the buoyant force exerted on an object, the density of the object, rather than the fluid, was used.	• $F_{\texttt{buoyancy on block}} = \rho_w V_b g$

	• In determining the buoyant force exerted on an object, the relevant density is that of the fluid that is displaced, not that of the object.
• The frequency of a wave changes when the wave enters a new medium.	• When the fluid in the tank is changed, the frequency of the beam of light will remain the same as before the fluid was changed.
• The speed and wavelength of a wave are inversely related.	• Because the speed of the light wave decreases when the medium is changed to one with a higher index of refraction, the wavelength will also decrease, as they are directly proportional.
• The d in the relationship $m\lambda = d\sin\theta$ is the separation between bright fringes of the interference pattern.	• Because m is an integer that indicates which fringe in the pattern is being considered and d is the separation between the slits in the block, neither of these quantities change. Therefore, because the wavelength has decreased, the angular separation between the fringes will decrease.
• The angle of refraction only depends on the medium the light is entering.	• The refraction that occurs at the boundary between two optical media depends upon the ratio of the indices of refraction of those two media.

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?

Instruct students that "derive" means to start from first principles. A good strategy is to start with a generally applicable equation from the equation sheet and substitute symbolic quantities and variables based on the specific problem to solve for the desired quantity.

Question 2

Task: Experimental Design
Topic: Electric Circuits, Resistors, and Capacitors
Max Score: 12
Mean Score: 5.59

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Differentiate between the potential difference across resistors that are connected in series and parallel.
- Calculate the amount of charge on a fully charged capacitor using data from an experiment.
- Use data to describe the arrangement of capacitors in a circuit, i.e., whether the capacitors are connected in series or parallel.
- Utilize the fact that the amount of charge stored on two capacitors in series is equal in order to analyze experimental data.
- Plot data with appropriate scaling, labeling the axes of a graph with the appropriate quantities and units.
- Draw a best-fit line using a straightedge that follows the trend of the data.
- Calculate the slope of a best-fit line using two points on the line.

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 demonstrated understanding of the differences between circuit elements connected in series and parallel.
- It is clear that students are generally comfortable with performing ranking tasks.
- Some students struggled comparing a series circuit to a parallel circuit. For instance, these responses showed the correct ranking of the potential difference of two resistors in a parallel circuit and the correct ranking of the potential differences of two resistors in a series circuit. However, the responses demonstrated difficulty comparing the resistors in parallel to the resistors in series.
- Responses showed that calculations involving data is a skill students are comfortable with. Most responses included units for calculated quantities, but there was some confusion as a result of one of the values involved in the calculation having a prefix, micro.
- Responses showed understanding that capacitors connected in series have the same charge on each capacitor.
- When asked to provide evidence for why the capacitors are connected in series, many students provided data that supported the claim that the capacitors were not connected in parallel.
- Graphing data was seen as a common area where students appeared to have gaps in skill. Axes often did not include the appropriate units. Use of less than half of the entire grid was a common skill gap.
- It was apparent that many students did not have a straight edge when drawing the best-fit line.
- Many responses did not use two data points to determine the slope of a best-fit line but often used just one point.

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 comparing potential differences of resistors connected in parallel to the potential differences of resistors connected in series.	• The potential difference across resistors connected in parallel are all larger than the potential difference across resistors connected in series when the circuits

	are connected to a battery with the same potential difference.
• Errors in calculations with a quantity that has a prefix before the unit and a quantity that does not have a prefix before the unit.	• $(200\ \mu F)(0.91\ \text{V}) = 182\ \mu\text{V}$
• Not labeling axes with both the quantity and the units, for instance, labeling an axis "Charge (Q)."	• $Q\ (\mu\text{C})$
• Drawing a best-fit line by hand, which does not accurately follow the trend of the data.	• Clear use of a straight edge/ruler to draw one distinct best-fit line that follows the trend of the data and includes approximately the same number of data points above and below the best-fit line.
• Calculating the slope of a best-fit line using a method based on only one data point. This would only be correct if the best-fit line passes through the origin.	• $\frac{y_2 - y_1}{x_2 - x_1} = \frac{212\ \mu\text{C} - 190\ \mu\text{C}}{4.10\ \text{V} - 3.67\ \text{V}} = 51.2\ \mu\text{F}$ • An ideal response would indicate the two points on the best-fit line that has been drawn and show a clear calculation of the slope using these points.

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?

- It is important to work with students to focus on the question that was asked. If the students are asked to discuss why capacitors are connected in series, the students should focus on how data shows that the capacitors are connected in series instead of why the capacitors are not connected in parallel. While this type of response was accepted, situations will not always be binary. It is important to respond to the question in the affirmative.
- Practice calculations involving prefixes and scientific notation.
- Students need to graph data by hand often. It was clear that this is a skill that is a common struggle for students.
  - Data from hands-on experiments should be graphed. Data sets can also be generated to graph quickly from simulation sites in order to help students focus on graphing skills without the distraction of data that may not produce a straight line.
- Calculating the slope of a best-fit line is also a skill to work on. Practice having your 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 the students show $\frac{y_2 - y_1}{x_2 - x_1}$ with values substituted when calculating slopes.
  - Provide students with pre-drawn graphs and have the students practice determining the slope of the line.

Question 3

Task: Qualitative-Quantitative Translation
Topic: Energy in Hydrogen Atom
Max Score: 12
Mean Score: 4.57

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Derive an expression for the speed of an electron orbiting a proton based on the relationship between the electrostatic force and centripetal acceleration experienced by the electron.
- Derive expressions for kinetic energy of an electron and electric potential energy of an electron-proton system.
- Apply functional dependence in mathematical relationships related to changes in orbital radius and energy.
- Calculate the energy of photons and mass-energy equivalence of electrons, and analyze student claims comparing the values.
- Create representations of potential and kinetic energy (using bar charts) after photon absorption.

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 indicated an understanding that the electric force between the two charged particles was the force responsible for the centripetal acceleration. The majority of those responses set $F_E = F_C = ma = m\frac{v^2}{r}$ to begin the derivation. However, a significant number of responses either incorrectly set the force directly equal to the acceleration ($F_c = a = \frac{v^2}{r}$), neglecting to use mass anywhere in the derivation, or left F_E in terms of Q and electric field E, which was not a quantity given.
- Many responses relied heavily on numerical substitutions of known constants (e.g., replacing m_e with 9.11×10^{-31} kg) instead of utilizing the values in symbolic quantity form throughout the derivation. This resulted in some unnecessarily complex and lengthy terms in derived expressions throughout part (a) and part (b).
- A significant number of responses started derivations properly but made important omissions (e.g., failing to include the Coulomb's law constant), incorrect substitutions (e.g., using mass of incorrect particle), or algebraic errors (e.g., replacing $q \times q$ with $2q$ instead of q^2).
- In most responses, students successfully substituted their expression for velocity into an expression for kinetic energy. While some responses successfully derived an expression for electric potential energy, very few responses listed the term as negative.
- Although most responses had an incorrect expression for total energy, the responses demonstrated a strong understanding of functional dependence between r and energy while comparing the expression to the statement in part (c).
- The majority of responses demonstrated a strong understanding of how to calculate photon energy, but many responses illustrated a lack of recognition of the importance of units (e.g., responses were calculated using Planck's constant in $\text{J}\cdot\text{s}$, with answers provided in the units of eV without proper conversion of units). When comparing to mass-energy equivalence in part (d)(ii), this issue pertaining to units created some discrepancies that some responses resolved with proper conversions of one value, but many responses did not resolve.
- Responses demonstrated a strong understanding of how to compare energy values from part (d)(i) to values in part (d)(ii), but occasionally showed comparisons between non-equivalent units. A small but not insignificant number of responses correctly listed c^2 in the equation but failed to actually square the value, resulting in incorrect values to compare.

- When creating representations of energy with a bar chart, responses demonstrate an understanding of the representation. Many responses indicated a correct $U_{E,f}$ or a correct $K_{E,f}$, but few responses indicated both correctly.
- Many responses in part (d)(iii) illustrate two bars with the same combined length as the initial sum, attempting to demonstrate conservation of energy but failing to recognize that U becoming less negative is an increase in energy and/or a lack of recognition that energy was added to the system by the absorption of the photon.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Stating $F = E$, $F = a$, or equating other non-equivalent terms, demonstrate a general lack of differentiating between variables on the equation sheet and which quantities variables and/or symbolic quantities represent.	• Responses that indicate acceleration is the result of a net force and including mass in the relationship (e.g., $F_E = \frac{mv^2}{r}$ rather than $F = \frac{v^2}{r}$).
• Assuming the law of conservation of energy means total energy of a system cannot change and/or potential energy U always equals kinetic energy K at any point.	• Recognizing that total energy includes the sum of K and U at any given time and also that energy can be added to the system from an outside source, which can increase the total energy of the original system.
• Using any expression for E to reference energy (including expressions for electric field).	• Only using energy expressions for derivations of energy.
• Incorrectly using mass of both particles when calculating K.	• Using only the mass of the moving particle (the electron) to determine K or using a separate term for the kinetic energy of the proton with a velocity of zero.
• Listing electric potential energy of an electron-proton system as positive.	• Recognizing the electron is bound in its orbit around the proton and listing the electric potential energy as a negative term.
• Assuming that a value approaching zero must always be decreasing (e.g., applied to a negative quantity, like potential energy).	• Recognizing that for a negative value (like U in this case), when the quantity has a smaller magnitude (i.e., is less negative), this corresponds to an increase in the quantity.
• Lack of consideration of units when selecting a numerical value for a needed constant.	• Responses that used the value of Planck's constant with units that would allow for comparison between energy in consistent units.

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?

- Encourage students to keep physical constants in symbolic quantity form to minimize unnecessary computations while deriving an expression.
- Emphasize the significance of electrical potential energy having a negative value and that even with the inclusion of kinetic energy, a system consisting of an orbiting object will still have a negative total energy.
- Emphasize the importance of units when comparing two quantities. If two quantities are calculated with different units, students should convert the quantities to equivalent units before comparing the values.

Question 4

Task: Short Answer
Topic: Magnetism and Electromagnetic Induction
Max Score: 10
Mean Score: 3.55

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Indicate that the magnitude of the electric force on a charged particle in an electric field is given by $|F_E| = |qE|$.
- Use the fact that the magnitude of the magnetic force on a charged particle moving perpendicular to a magnetic field is given by $|F_M| = |qvB|$.
- Apply the relationship $B = \frac{\mu_0 I}{2\pi r}$ for the magnetic field created by a long, straight current-carrying wire.
- Apply Faraday's law to changing magnetic flux through a conductive loop of wire to analyze induced emf (potential difference) and current in the loop.
- Calculate the induced current using Ohm's law and induced emf (potential difference), which depends on the rate of change of flux in a loop.

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 responses showed familiarity with calculating emf from changing flux in addition to calculating current from potential difference and resistance.
- Overall, responses showed a good understanding of the expectations of the task verb "calculate." Many responses showed clear steps indicating equations and substitutions.
- Responses demonstrated less understanding of what is required by the "derive" task verb. Many responses began with an expression unique to the physical situation presented rather than a fundamental principle.
- In many cases, it was observed that principles that were potentially understood by the students were not clearly and completely communicated on the pages of the exam. In the case of part (c), many responses referenced events happening either due to or in "the coil" without specifying which coil was being referenced.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Using the incorrect equation for electric force on a charged particle in an electric field of known magnitude E. Many attempts to use $\left\|\vec{F}_E\right\| = \frac{\|kq_1q_2\|}{r^2}$ were observed.	• Because the electric field was given with magnitude E, the electric force on the charged particle is given by $\left\|\vec{F}_E\right\| = q\left\|\vec{E}\right\|$.
• Making the erroneous assumption that magnetic fields are only created by *changing* currents.	• Any moving charge creates a magnetic field. Therefore, a current, which is a collection of moving charges, creates a magnetic field. If the current is in a long straight wire, the magnetic field is given by $B = \frac{\mu_0 I}{2\pi r}$.

	If the current changes, the magnetic field will change, but the current does not have to change to create a magnetic field.
• Making the erroneous assumption that magnetic fields must be *changing* to cause a flux.	• Magnetic flux is a magnetic field passing through an area: $\Phi_B = \left\lvert\vec{B}\right\rvert \cos\theta \left\lvert\vec{A}\right\rvert$. Flux exists if a magnetic field passes through an area. Flux changes if the magnetic field, area, or alignment between the magnetic field and area changes.
• Making the erroneous assumption that flux (rather than changing flux) induces current.	• An emf is induced (and charged will flow in a conductor) when magnetic flux changes. The emf can be calculated by $\varepsilon = \frac{\Delta\Phi_B}{\Delta t}$. If flux is nonzero, but constant, then $\Delta\Phi_B = 0$ and there is no induced emf and, therefore, no induced current.

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?

- Teachers should help students compare and contrast gravitational, electric, and magnetic forces on particles in fields.
    - Encourage students to determine if a given particle is acting as the source of the field or experiences a force due to the presence of a field in the scenario.
    - Because students are most familiar with the gravitational force (F_g) on a mass (*m*) in a gravitational field (*g*), help the students observe the parallel to the electric force (F_E) on a charge (*q*) in an electric field (*E*). This concept can then be expanded upon to consider a moving charge in a magnetic field.
        - $F_g = mg$
        - $F_E = qE$
        - $F_M = qv\sin\theta B$
- Encourage students to be specific and precise with language when forming arguments.
    - In the case of an inversely proportional relationship, do not simply calculate ratios without first referencing the physical principle/relationship the ratio is based upon.
    - When multiple objects are involved in a scenario, make it clear which object is being referred to. In the case of this question, there were two coils, a round coil and a square coil.