Chief Reader Report on Student Responses:

2023 AP® Physics 2: Algebra-Based Free-Response Questions

• Number of Students Scored	20,453		
• Number of Readers	624 (for all Physics exams)		
• Score Distribution	Exam Score	N	%At
	5	3,377	16.51
	4	3,774	18.45
	3	7,131	34.87
	2	4,862	23.77
	1	1,309	6.40
• Global Mean	3.15		

The following comments on the 2023 free-response questions for AP® Physics 2: Algebra-Based were written by the Chief Reader, 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: Short Answer
Topic: Optics, Refraction
Max Score: 10
Mean Score: 6.05

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Relate the refraction of light passing from one medium to another to the indices of refraction of the two media.
- Relate the index of refraction of a medium and the wavelength of the light in the medium.
- Use Snell's law at an interface between two optical media, including demonstrating an understanding of the correct normal line.
- Apply Snell's law for multiple sequential interfaces between optical media and rank the resulting angles of refraction at each interface.
- Predict path changes for a beam of light entering and exiting a tank filled with layers of liquids of varying indices of refraction.

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?

- Virtually all responses correctly identified the change in direction of the refracted beam of light passing from air into water. Most responses indicated the correct direction of refraction as light traveled from water to air, but this second refraction was omitted in a notable number of responses.
- Most responses correctly identified that the wavelength of light decreases when passing from a material with a lower index of refraction to one of higher index. While not required, many identified constant frequency and decreased velocity of light to be the cause of that change. However, a sizable number of responses confused the terms "wavelength" and "beam" and therefore described the refracted path of the light instead of the change in wavelength.
- Most responses correctly applied Snell's law to at least two boundaries in the layered tank. A large number of responses correctly compared the top layer to the bottom layer with no intervening layers.
- Most responses incorrectly ranked the angles of refraction through the layered tank. By far, the most common incorrect ranking was "1234," with a smaller but significant number ranking them "2134." Because many students had correct explanations following their incorrect rankings, there may have been confusion about which angles were being ranked, as angle θ_1 was in Model A on the left, but $\theta_i, \theta_2, \theta_3$, and θ_4 were in Model B on the right, and students may have mixed them up.
- In the explanation of these rankings in part (c)(ii), most responses correctly identified the inverse relationship between indices of refraction and angles of refraction, but many responses either explicitly or implicitly related the size of the angle of refraction to the number of refractions rather than the index of refraction of each material (i.e., "lower" layers resulted in smaller angles of refraction, even if two materials had the same index of refraction). Some responses explained the ranking as the result of the *difference/change* in index of refraction at the interface; thus, saying that θ_1 was the largest angle because the change in n was the greatest from n_a to n_m.
- When modeling the exit positions of the light beams in each tank, most responses correctly predicted that d_A would be less than d_w, but a significant number stated that d_B would be greater than or equal to d_w either because the top layer in Model B was water or because the refractions are reversed as the light refracts back up through the layers.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Refraction angles are additive: Given the same angle of incidence in air, a light ray traveling from air to another material will result in different angles of refraction depending upon how many other layers are above that material. The "lower" the layer, the smaller the angle of refraction.	• The angle of refraction depends only on the indices of refraction of the two media and the angle of incidence at the top surface. The angle of refraction depends upon the *ratio* of the indices of refraction between two layers.
• Refraction angles depend upon the difference in index of refraction between the two materials at an interface, so $\theta_1 > \theta_3$.	• $\theta_1 = \theta_3$ because both are in materials with the same index of refraction n_m.
• The wavelength of light is refracted toward the normal when it passes from air into a medium of higher index of refraction. ("Wavelength" is synonymous with "beam.")	• Wavelength is inversely proportional to index of refraction. If n increases, the wave slows down and the wavelength decreases.
• The position of a light beam exiting a tank with multiple layers depends only upon the index of refraction of the top layer, i.e., $d_B = d_w$, because after reflection on the bottom of the tank, the light is "unrefracted" as it returns back to a substance of lower n. Only the top layer matters, which is the same n_w in the original tank and Model B.	• $d_A < d_w$ and $d_B < d_w$ because the index of refraction is larger overall for both Model A and B; the light beam bends more towards the normal as it travels down through the tank, traveling a smaller horizontal distance than in the tank with only water.

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 read questions carefully. A number of students missed the fact that the first tank contained a mirror at the bottom and drew the light ray as if it were passing through a glass block.
- Emphasize that refraction results not only in a new path for a light ray but also a different wavelength and that the term "wavelength" is not synonymous with "wave" or "beam."
- Demonstrate that because Snell's law expresses ratios of $\sin(\theta)$ and n, one can compare refraction angles in a series of layers simply by comparing indices of refraction.

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 6 on Refraction, Reflection, and Absorption.
- Teachers should direct students to Higher Ed Faculty Lectures on Unit 6.
- 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: Experimental Design
Topic: Electric Circuits, Capacitors, and Nonideal Battery emf
Max Score: 12
Mean Score: 6.30

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Complete a circuit diagram to use in an experiment to determine the identity of an unknown circuit component.
- Describe an experiment to properly collect data about the electric circuit over a period of time.
- Demonstrate understanding of the decrease in the current in an RC circuit and the increase of the potential difference across a capacitor while a capacitor is being charged.
- Write a Kirchhoff's Loop Rule equation to describe a circuit that includes a nonideal battery that has internal resistance.
- Recognize how Kirchhoff's Loop Rule equation can be used to determine the emf of the battery by selecting the appropriate variables to graph.
- Plot data with appropriate scaling and label 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.
- Use the graph and appropriate equation to determine the emf of a nonideal battery.

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 showed an understanding that a source of potential difference (battery or power supply) was needed to complete the circuit, but many responses did not include a measurement device to measure the current in the circuit or the potential difference across the circuit component.
- Some responses utilized a multimeter to take measurements of the circuit without specifying if it was being used as an ammeter or voltmeter.
- Most responses showed that data needs to be collected over time to determine if the circuit component is a capacitor.
- Many responses did not support the results of the experiment with both a discussion of potential difference and charge or current but only discussed one aspect of the experiment.
- Most responses expressed a correct equation that applied Kirchhoff's Loop Rule in terms of the given variables.
- Many responses struggled with using the Loop Rule equation to determine what quantities to graph that would yield a straight line that could be used to calculate a value for the emf of the battery.
- Responses showed improved graphing 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*
• Incorrectly drawing ammeters in parallel with the circuit component or voltmeters in series in the circuit on a circuit diagram.	• Correctly drawing an ammeter in series in the circuit and/or a voltmeter in parallel with the circuit component.

• Only taking one measurement.	• Taking measurements of the circuit over time or after a long time.
• Mixing up circuit terms or using them interchangeably, such as discussion of voltage flowing through wires or the current varying from one position in a circuit to another.	• Discussing current in the circuit and potential difference across the circuit component.
• Describing the current as decreasing from one side of a capacitor to another.	• Describing the current at a point in time being the same everywhere in a series circuit.
• Identifying quantities that when graphed yield an inverse relationship and not a straight line.	• Recognizing what quantities could be graphed to yield a straight line and properly linearizing the data to plot and yield a straight line.
• Not labeling axes with both the quantity and the units or not having the units match the quantity. For example, graphing $1/\text{current}$ and listing the unit as A instead of $1/\text{A}$.	• Properly labeling both axes with the appropriate quantities and matching units.
• Only using a small portion of the provided graph space to plot the data.	• Choosing a scale that results in data points spread over more than half the area provided to plot the data.
• Drawing a best-fit line by hand, which does not accurately follow the trend of the data.	• Use of a straight edge/ruler to draw one distinct best-fit line that follows the trend of the data.

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 so they focus on the question that is being asked. If students are asked to refer to the circuit equipment in the diagram, make sure that they do so. If students are asked to support their answer in terms of both potential difference and charge, it is necessary to discuss both aspects of the circuit. If students are asked to use the graph to determine the emf of the nonideal battery, they should use either the slope or y-intercept, not just a data point from the data table.
- Have students manipulate equations to determine quantities that can be graphed to yield a straight line and determine how that graph will provide the requested information.
- Students need to graph data by hand often. It was clear that this is a skill that, while it is improving, is still a struggle for many students. It is also important to graph data that is in decimal form, like $0.016\ \text{A}$ and $0.087\ \text{A}$.
    - Data from hands-on experiments should be graphed. Data sets can also be generated to graph quickly from simulation sites to help students focus on graphing skills without the distraction of data that may not produce a straight line.

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 4 on Kirchhoff's Loop Rule and Kirchhoff's Junction Rule and the Conservation of Electric Charge.
- Teachers should direct students to Higher Ed Faculty Lectures on Unit 4.
- 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: Qualitative-Quantitative Translation
Topic: Fluids
Max Score: 12
Mean Score: 4.83

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Describe the microscopic cause of the buoyant force in terms of particle collisions on the upper and lower surfaces of a partially submerged object.
- Analyze the buoyant forces on partially submerged objects to compare the density of objects.
- Derive mathematical expressions that model the behavior of flowing fluids from Bernoulli's equation and the continuity equation.
- Analyze given mathematical expressions to determine the functional dependence between changing variables such as surface height, radius, and speed of water as it flows from a tank.

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?

- It was clear students were familiar with the basic principles of buoyancy and conservation principles in flowing fluids, i.e., Bernoulli's equation and the continuity equation.
- While it was apparent students had a basic knowledge of buoyancy, they often did not explain the aspects of the buoyant force that the prompt in part (a)(i) requested (the cause of the buoyant force in terms of the particle collisions).
- In part (a), a number of responses attempted to use reasoning based on a block that was accelerating when the prompt specified that both blocks were floating at rest.
- Although many responses indicated the density of Block A was greater than the density of Block B in part (a)(ii), the response was often connected to an incorrect claim about the buoyant force on each object or simply restated information given in the prompt, rather than correctly connecting the given information to buoyant force or volume of displaced water.
- Overall, responses showed a good understanding of the expectations of the "derive" task verb. Responses generally started with a fundamental principle and accurately incorporated specifics from the problem.
- Responses indicated a lesser understanding of the amount of detail needed to justify a claim. For example:
  - In part (a)(ii) responses often indicated that things that sink further must be more dense without any sort of physical justification for the claim.
  - In part (b)(iii) many responses indicated that the term v_s was "not needed" under the described conditions but did not provide a physical justification as to why the term would have a negligible effect on v_p.
- While the purpose of part (c) was to use equations from parts (b)(i) and (b)(ii) to justify a claim, many responses made claims about the speeds v_p and v_s and supported them with reasoning based on fundamental principles, rather than addressing the functional dependence in the equations from parts (b)(i) and (b)(ii).

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 buoyant force arises as a result of only the fluid beneath an object.	• The buoyant force is the net upward force on an object that results from the collisions from the fluid particles surrounding the object. While there are forces on the object in all directions normal to the surface, the particles beneath the object exert a greater upward force than the downward force from particles above the object.
• There is only a buoyant force on an object if the density of the object is less than the density of the fluid in which it is submerged (i.e., if the object floats).	• Whether or not an object floats or sinks, there will be a buoyant force on any object that is submerged or partially submerged in a fluid.
• Objects with the same dimensions must experience the same buoyant force when floating.	• The buoyant force on an object is equal to the weight of the fluid it displaces. When an object is floating in equilibrium, the buoyant force is equal to the weight of the object. Therefore, for floating objects, the weight of the object is equal to the weight of the fluid it displaces. If an object displaces a greater volume of fluid, it experiences a greater buoyant force. If two objects are floating, then the one with the greater buoyant force weighs more.
• Flow rate must remain constant over time.	• The flow rate at any two locations in a connected flowing fluid must be the same at any moment in time, but this rate can change in time.

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?

- Practice derivations beginning from fundamental principles and substituting given variables.
- Make sure students understand the specific purpose of the types of free-response questions. The purpose of the Qualitative-Quantitative Translation is for students to connect qualitative claims based on physics principles to a mathematical representation of the same principle. Students should anticipate that parts of the question will prompt them to address the dependence of one (or more) variables on another in a function. While they may be able to provide a physics principle to support their claim, the practice being assessed is the ability to connect a mathematical argument to the physics principle.
- Students should practice using specific language. In the case of this question, there were two speeds (the speed v_p at which the water exits the pipe and the speed v_s at which the surface of the water moves downward) and two radii (the radius R at the surface and the radius r at the pipe). Students commonly made references to the “speed” and “radius” without indicating which speed or radius they were referring to.

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 on Buoyancy and Conservation of Mass Flow Rates in Fluids.
- 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 4

Task: Paragraph-Length Response
Topic: Electric Field and Potential; Work and Energy
Max Score: 10
Mean Score: 3.45

What were the responses to this question expected to demonstrate?

The responses to this question were expected to demonstrate the ability to:

- Identify the relationship between a symmetrical distribution of charged particles and the types of charged particles to find the resulting electric field at the center of that particle distribution.
- Identify the relationship between the types of charged particles and their arrangement to find the electrical potential at the center of that particle distribution.
- Evaluate and critique the accuracy of a given statement through a concise, logical argument, using correct and appropriate physics.
- Represent the work required to move particles with positive and negative charges from very far away to the center of a particle distribution using bar charts.
- Represent the potential energy of a system of positively and negatively charged particles using a bar chart.

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 correctly evaluated Student Y's statement using the symmetry of the charge distribution to determine the value of the charge that needed to be placed at the empty vertex. A small number of responses correctly evaluated the vector components of the electric field from each charged particle to determine the required charge. Some incorrect responses mistakenly suggested that a "negative electric field could cancel out a positive electric field." Similarly, other incorrect responses demonstrated a lack of understanding of vector addition, while others confused and/or conflated electric potential with electric field. For example, some responses claimed that because there was an electric field from Particle A (incorrectly written as kQ/r) and an electric field from Particle B (incorrectly written as kQ/r) at Point P, then the resulting field from these charges had to be $2(kQ/r)$ which could only be counteracted by an electric field from a $+2Q$ charge. Surprisingly, for a question that dealt with an application of vectors, few responses showed vector drawings.
- More responses were able to correctly address Student Z's statement than Student Y's, most likely because electric potential is a scalar quantity. Responses correctly evaluated the electric potential in terms of the value of the charges present. Responses also directly stated electric potential is a scalar quantity. Incorrect responses conflated the total charge as the electric potential.
- Responses generally indicated an understanding of how to draw the bar charts in part (b)(i). Most responses correctly recognized that the work done was positive. The most frequently missed point on the entire question was recognizing the final energy of the system is three times the value of the initial energy of the system. Even if the middle point was missed, most responses correctly showed an understanding of the relationship between the work done on the system and the initial and final energies.
- Incorrect responses seemed to stem from the misunderstanding of how potential energy is found in a collection of charges. This can be reflected in the incorrect responses drawn on the bar charts. For part (b)(i), this includes failing to realize that bringing in a $+Q$ charge to the empty vertex would mean calculating the potential energy from three pairs of charges. This could explain why so many responses failed to show $U_{1f} = 3U_{1i}$. The results for part (b)(ii) were similar; responses generally demonstrated understanding that the work and the initial potential energy added together had to be the final energy, but they failed to recognize the final energy of the system was the negative of the initial energy.

- Incorrect responses for parts (b)(i) and (b)(ii) showed either bar charts being drawn well above or well below and not touching the x-axis. Other responses drew three charts per section, which could have been a misunderstanding of what U_{i1}, U_{f1}, W_1, U_{i2}, U_{f2}, and W_2 represent.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Responses refer to the force on Point P instead of an electric field at Point P. • Responses that use the words repel or attract instead of vector representation. • Responses that referred to or discussed the forces between the charged particle pairs (A and B, etc.). • Responses refer to where the "charge points to ..." instead of the electric field due to a charged particle. • Responses that referred to the "components of charge." • Responses that conflate the summation of charges as resulting vector sums. • Responses that show a misunderstanding of the symmetry and the arrangement of charged particles.	• Responses that referred to a force on a hypothetical particle placed at Point P that points in a particular direction were able to get credit for the vector point. • Responses that referred to the electric field in relation to the force on the particle at Point P. • Responses that referred to the components of the electric field from individual charges and the vector summation of those components to give a resulting vector. • Responses that included diagrams with vectors representing the components of a charged particle's electric field and the proper vector summation. • Responses that included equations relating the electric field to the charge such as: $\vec{E} = \vec{F}/q$.
• Responses that confuse and/or conflate electric potential for electric field. • Responses that refer to the summation of charges without relating the result to electrical potential. • A few responses only discussed or referred to Student Y and neglected to mention anything about Student Z.	• Responses that referred to the summation of charges and then showed how that value was related to electric potential at a point. Many good responses used something like: $\frac{k(Q+Q-Q)}{r}$ or $\frac{k(Q+Q-2Q)}{r}$ in the answer. • Responses that specifically stated electric potential is a scalar quantity and is proportional to the charge of the particle. • Responses that stated $(Q+Q-Q) \neq 0$ or $(Q+Q-2Q) = 0$ and later made the connection to electric potential.
• Responses for part (b)(i) didn't recognize that the final potential energy of the scenario is three times the value of the initial potential energy of the system. • The most commonly missed point on this problem was the point for showing the final energy of the system was three times the initial energy of the system. Many	• Responses that showed a positive work W and a correct representation of work/energy conservation could still earn points, even if the response didn't show the correct relationship between the initial and final energies. • Bar graphs that were erased and redrawn made evaluating the response more difficult. If revisions were

responses didn't make the connection that work/energy is due to pairs of charges, not due to a single charge. • Responses for this part did not begin the bar charts on the x-axis at 0. Some charts began several grid blocks below or above the axis (floating charts).	needed, responses that redrew bar charts and included notes indicating what portion to score and what portion to ignore were able to communicate the intended answers more effectively.
• Responses for part (b)(ii) didn't recognize the final energy of the system is the negative of the initial energy of the system. • Responses for this part didn't recognize the fact that the values of all three bars should reflect the change in energy of the system • For both part (b)(i) and part (b)(ii), a few responses misconstrued the three columns in each section to represent the energy (and work) of the three individual particles. Some responses gave three bar charts per section. • Responses for this part did not begin the bar charts on the x-axis at 0. Some charts began several grid blocks below or above the axis (floating charts).	• Correct responses showed bar charts that correctly represented the change in energy of the system. • Responses that gave a negative value for work, even if that was an incorrect value, could still earn the conservation of energy point if $U_{i2} + W_2 = U_{f2}$.
• Responses often referred to Student X rather than Student Y or Z. Some responses confused the arguments.	• Correct responses matched analyses of statements made by Students Y and Z with the claims made by Students Y and Z.

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?

- To be more successful on the energy conservation bar charts, it's suggested that teachers emphasize how to define a system. Incorrect responses showed a weaker understanding of what a system is, how to properly define it for the questions, and how to determine the change in energy by the work done. For conservation of energy to be used, the system is defined in such a way that there are no external forces. In other words, everything that's causing a force on every other part of the system will be part of that system. For work-energy to be used, the system should be defined such that any external forces are doing work on the system.
- When making a mistake while drawing bar charts that would lead to significant revision, a suggestion would be to redraw the chart in a different location than where the mistake was made and make a note.
- Emphasize the use of drawing vectors to represent the electric field lines from charged particles at a point in space. Emphasize the use of vector components to add electric fields.
- Demonstrate and explain the relationship between electric field, electric force, and electric potential due to a single charged particle and due to a collection of charged particles.
- The relationship between work and energy can be confusing with charged particles of different signs but establishing a well-defined system before trying to determine the change in energy/work serves to establish a reference point that is very helpful and mitigates confusion.
- Discuss the importance of symmetry when working with distributions of charged particles and electric fields.
- Use something like PhET simulations to demonstrate work/energy bar charts and electric field and electric potential diagrams.
- Emphasize good handwriting and remind the student to reply to the question that's being asked.

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 on Electric Systems, Electric Forces and Free Body Diagrams, and Conservation of Electric Energy.
- 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.