# Chief Reader Report on Student Responses:

## 2024 AP® Physics 1: Algebra-Based Free-Response Questions

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|---|---|---|---|
| • Number of Students Scored | 164,481 | | |
| • Number of Readers | 685 (for all Physics exams) | | |
| • Score Distribution | Exam Score | N | %At |
| | 5 | 16,725 | 10.2 |
| | 4 | 29,405 | 17.9 |
| | 3 | 31,652 | 19.2 |
| | 2 | 42,981 | 26.1 |
| | 1 | 43,718 | 26.6 |
| • Global Mean | 2.59 | | |

The following comments on the 2024 free-response questions for AP® Physics were written by the Chief Reader, Brian Utter, 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:** Conservation of Energy
**Max Score:** 7
**Mean Score:** 4.58

### *What were the responses to this question expected to demonstrate?*

The responses were expected to demonstrate the ability to:

- Recognize and apply the principle of conservation of energy through multiple representations including an energy bar chart and a mathematical derivation.
- Construct a free-body diagram to show the gravitational and normal forces.
- Identify how a changing height affects the gravitational potential energy and kinetic energy at different positions.
- Demonstrate an understanding as to how velocity and kinetic energy can affect an object moving in a loop and experiencing centripetal acceleration.
- Construct an explanation to support a claim made in the prompt and give evidence as to why the original claim was incorrect.

### *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?*

- In general, the responses demonstrated mastery of conservation of energy and energy bar chart representations. Roughly 90 percent of responses had both bars with magnitudes totaling 6 units.
- Approximately 80 percent of the responses in part (b) began with a representation of conservation of energy and attempted to derive an expression for the speed of the block at Point B.
- More than half of the responses substituted initial and final heights correctly or substituted heights consistent with their bar charts from part (a) into an equation.
- 95 percent of the responses were able to correctly draw and label the force of gravity as a downward vector.
- About half of the responses were able to correctly draw and label the normal force as a downward vector.
- About half the responses identified that there was insufficient kinetic energy, and thus speed, to complete the loop.

### *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 split the energy in the bar chart evenly between kinetic and gravitational potential energy at Point B in the bar chart but did not continue with the reasoning later in the prompt.<br>• Responses drew a bar with 6 units to indicate that all energy was kinetic at Point B, and some responses did continue with this reasoning later in the prompt for the derivation. | • Responses correctly drew an energy bar chart with 2 units for gravitational potential energy and 4 units for kinetic energy. |

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| • Responses began with a statement of conservation of energy but used algebra incorrectly to determine a final answer. | • A correct response had a conservation of energy statement and included correct substitutions for the heights, consistent with an answer in part (a). $mgh_A = mgh_B + \frac{1}{2}mv^2$ $Mg(6R) = Mg(2R) + \frac{1}{2}Mv^2$ $v = \sqrt{8gR}$ |
| • Responses had a vector representing the net centripetal force on the free-body diagram. When included, the net centripetal force was drawn in multiple directions in various responses, but the most common direction was downward.<br>• Responses had a vector labeled for the normal force that was pointing upward.<br>• Responses labeled extraneous vectors on the free-body diagram, such as friction, motion, kinetic energy, or momentum. | • Correct responses for the free-body diagram in part (c)(i) drew one downward arrow labeled "$F_g$" and a separate downward arrow labeled "$F_n$" or other acceptable labels representing that the box was only interacting with the Earth and the surface of the track. |
| • Responses did not calculate the height of Point C correctly, often using the height as $3R$ instead of $4R$.<br>• Responses in part (c)(ii) began the reasoning by identifying the gravitational potential energy at Points A and C, but did not proceed to the final proper reasoning addressing the velocity or kinetic energy of the block.<br>• Responses indicated that the energy of the block-Earth system would decrease or be "lost" as the block traveled through the loop. | • Responses correctly stated that there would only be gravitational potential energy at Point C, so there would be no kinetic energy at Point C due to conservation of energy. The speed would be zero, and the block would lose contact with the track. |

***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?***

- The AP 1 workbook has scaffolding for derivation practice. The workbook suggests a two-column chart where the words for each step are on the left side, and the math steps are on the right. The AP Physics 1 workbook pages that would help students prepare for this question are 3D, 3E, and 4G.
- For energy bar charts, use them often in class discussion as an alternative model or representation of energy for various systems throughout the year. This can help with applications both with and without mathematical representations. Practice energy bar charts using card sorts matching situations with their appropriate energy bar charts. Universe and More has a great interactive practice with energy bar charts in different designated systems.
- For derivations, model this practice on the board for students throughout the year. Starting more so in the fall and tapering off in the spring when students can use other scaffolded activities to guide this process. Have students practice derivations with groups on whiteboards and follow up with individual practice.
- For derivations, type up a derivation step by step. Print it out and cut it up. Provide students with the cut-up derivation and ask them to put the cards in the correct order and justify their work.
- The Physics Classroom has a free-body diagram simulation that can be used to help students work more independently on these diagrams while receiving instant feedback about their misconceptions.
- Practice "justify" steps using multiple modalities for students. Use turn and talk, think/pair/share, peer-reviewing, presenting, or selecting correct student responses as activities to support this skill.

***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 AP Daily videos on Energy, Uniform Circular Motion, and Forces.
- Teachers should assign topic questions as well as personal progress check items to monitor progress being made in the mastery of content.
- Additional questions involving Energy, Uniform Circular Motion, and Forces can be found in the AP Physics 1 student workbook. These scenarios help students practice using the ideas of conservation of energy and re-expressing physical phenomena with bar charts.

## Question 2

**Task:** Experimental Design
**Topic:** Dynamics
**Max Score:** 12
**Mean Score:** 7.34

### *What were the responses to this question expected to demonstrate?*

Responses were expected to demonstrate the ability to:

- Communicate a procedure to measure a quantity using a specified set of equipment.
- Identify a pair of variables that could be plotted to create a linear graph whose slope would help determine the spring constant (e.g., mass and the square of period).
- Calculate the change in kinetic energy of an oscillating object from a velocity versus time graph.
- Estimate the change in momentum from a force versus time graph using the area under the graph.
- Calculate the change in momentum from a velocity versus time graph using speeds at specific times.
- Demonstrate consistency between different representations of motion.

### *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 were able to design an experiment with limited lab equipment and describe a procedure using that equipment. Approximately 75 percent of students described an experiment including an oscillating mass. Other responses attempted to use Hooke's law, which indicates that some test-takers did not notice the word "only" describing the given materials in prompt on the first page.
- Generally, responses contained great answers to part (b). Test-takers typically identified variables that would produce a linear graph and were able to manipulate an equation to find a spring constant using the graph's slope.
- For part (c)(i) most responses included a written equation for the change in kinetic energy, substituted values correctly, and arrived at a correct numerical answer.
- For part (c)(ii) many test-takers had difficulty estimating a change in momentum using the area under a graph of force as a function of time.
- Even though test-takers were able to use the force versus time graph and the velocity versus time graph separately, it proved challenging for them to discuss the consistency between the two different graphs.

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

- Many responses said to measure the time for an oscillating spring to travel from the top to the bottom of its bounce rather than measure one full period.
- Many responses indicated that the instantaneous momentum of an object is the product of the net force exerted on the object and what time it is relative to a zero. That is, test-takers clearly think that $p = Ft$ rather than $\Delta p = F_{\text{average}} \Delta t$.
- Responses showed a lack of understanding of how to compare the slope of a line to an unknown quantity.
- Many responses showed a misunderstanding of how to calculate the change in a quantity.

| *Common Misconceptions/Knowledge Gaps* | *Responses that Demonstrate Understanding* |
|---|---|
| • Responses incorrectly indicated that for an object oscillating at the end of a spring, the time it takes the object to travel from the top to the bottom of the oscillation is a whole period. | • Correct responses indicated to "use a stopwatch to time the cylinder on the spring as it travels to the lowest point and stretches the spring. Then double that time to determine the period." |
| • Responses incorrectly indicated that the change in kinetic energy can be calculated with $\Delta K = \frac{1}{2}m(\Delta v)^2$ rather than $\Delta K = \frac{1}{2}m\Delta(v^2)$ | $K = \frac{1}{2}mv^2$<br>$\Delta K = \frac{1}{2}mv_f^{\,2} - \frac{1}{2}mv_i^{\,2}$<br>$\Delta K = \frac{1}{2}m\left(v_f^{\,2} - v_i^{\,2}\right)$<br>$\Delta K = \frac{1}{2}m\Delta(v^2)$ |
| • Responses showed difficulty describing how to use the slope of a linearized graph to determine an unknown quantity. | • Correct responses indicated to plot $4\pi^2 m$ on the vertical axis and $T^2$ on the horizontal axis.<br>• Correct responses indicated that the slope of the best-fit line is equal to *k*. |
| • Many responses indicated that the instantaneous momentum of an object is the product of the net force exerted on the object and what time it is relative to zero. That is, test-takers indicated that $p = Ft$ rather than $\Delta p = F_{\text{average}}\Delta t$ . For example, the responses indicated that the momentum at $t = 2.0\ \text{s}$ is $p = Ft = (0.8\ \text{N})\cdot(2.0\ \text{s}) = 1.6\ \text{N}\cdot\text{s}$. | • Correct responses equated the change in momentum to the area under a graph of force as a function of time.<br>• Correct responses equated the change in momentum to the average force exerted during a time interval multiplied by the time interval. |

***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?***

- The AP Physics 1 Workbook is a scaffolded collection of bite-sized practice pages. It helps students practice experimental design, linearization of data, and understanding simple harmonic motion graphs. The following pages would have been particularly useful in preparing students for this problem: 6A, 6C, 6D, 6 E, 6 H, 6I, 5D, and 5H.
- Ensure that students are practicing designing and performing laboratory experiments multiple times per unit.
- Ask students to design an experimental procedure using limited equipment, so that they are used to working within constraints of available measuring devices.
- Have students practice linearizing data and using the graph to complete analyses for different scenarios. This graph practice can be completed on whiteboards with a small group to start and then move to completing this process individually.
- Incorporate "mini-labs" where students can use their lab skills to compete and calculate an unknown quantity using their measurements.
- Have students practice writing experimental procedures and have another group try to follow and give feedback on those experiments.
- Have students use virtual simulations like Phet Springs and Masses, as well as physical experiments.

- At the end of the school year, the "AP Daily Live Review" videos provide reviews on particular question types. These videos outline the skills students need to demonstrate on the exam.

***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 AP Daily videos on Simple Harmonic Motion, Hooke's Law, and the Impulse-Momentum theorem.
- Teachers should assign topic questions as well as personal progress check items to monitor progress being made in the mastery of content.
- Additional questions involving Simple Harmonic Motion, Hooke's Law, and the Impulse-Momentum theorem can be found in the AP Physics 1 student workbook. These scenarios help students practice using the ideas of simple harmonic motion, the impulse-momentum theorem, and justifying consistency between representations.

## Question 3

**Task:** Qualitative-Quantitative Translation
**Topic:** Equilibrium
**Max Score:** 12
**Mean Score:** 5.04

### *What were the responses to this question expected to demonstrate?*

The responses were expected to demonstrate the ability to:

- Identify and label the forces exerted on a beam in equilibrium.
- Draw the directions of forces such that the net force and net torque sum to zero.
- Compare the relative magnitudes of the tension force provided by the string in two different scenarios using qualitative reasoning.
- Derive an expression for the tension in the string beginning with Newton's second law in rotational form.
- Evaluate consistency between stated reasoning based on a qualitative argument and a derived equation.
- Sketch the angular speed as a function of time for a rigid rod rotating about one end due to the gravitational force.

### *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?*

- About 70 percent of responses were able to draw a force diagram with the correct directions for the gravitational and tension forces exerted on the beam. About 30 percent of responses showed the beam in translational equilibrium, although the forces rarely (<20 percent) resulted in rotational equilibrium by correctly drawing the force at the hinge. A small percentage of responses did not draw force vectors starting on and extending away from the beam.
- About 70 percent of responses were able to correctly indicate that the tension in the string will increase when attached lower on the wall. Responses generally were able to make some relationship between the tension force and the angle of the string, although responses less frequently (30 percent) related that the vertical component of the tension force remains constant to balance the weight of the beam or to the requirement that the net torque remain the same.
- About 50 percent of responses were able to utilize a multi-step derivation to obtain an expression for the tension force in terms of $\theta$.
- About 80 percent of responses did a good job of attempting to connect their qualitative response to their derivation. Responses need to be specific about the features of the functional dependence as it relates to the rationale utilized in part (b).
- About 90 percent of responses correctly indicated that the angular speed of the beam continuously increased after the string was cut, although responses were rarely correct (20 percent) about the decreasing rate of change in the angular speed with respect to time.

***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 frequently placed the beam in translational equilibrium by drawing the force from the hinge as a horizontal vector. This force did not result in the system maintaining rotational equilibrium.<br>• Around 20 percent of responses had extraneous forces (normal force), drew only the components of the tension force on the string, or did not include labels on the vectors.<br>• Fewer responses drew the gravitational force or the hinge force at the right end of the beam. | • Correct responses indicated the hinge force was exerted at the location of the hinge and was directed upward and to the right for the system to remain in rotational equilibrium in addition to translational equilibrium.<br>• Correct responses indicated only three vectors (not components) exerted on the beam.<br>• Correct responses indicated the gravitational force exerted at the center of the beam, directed downward, and the tension force exerted on the right end of the beam directed along the string. |
| • Responses selecting "$F_{T2} = F_{T1}$" frequently did not distinguish between the vertical components of the tension force remaining equal and the magnitude of the tension force.<br>• Responses selecting "$F_{T2} < F_{T1}$" frequently used a justification that the shorter length of string results in a smaller tension force.<br>• A small fraction of responses provided a justification opposing their selected comparison of tensions, possibly misinterpreting the "greater than" and "less than" symbols. | • Responses demonstrating correct understanding recognized the vertical component of the tension force remains unchanged, and, therefore, with a smaller angle, the magnitude of the tension must increase.<br>• Alternatively, responses demonstrating correct understanding recognized the sum of torques remains zero; therefore, the torque due to the tension force is the same. If the angle between the tension force and the beam decreases, then the tension force must increase to compensate. |
| • Although responses identified Newton's second law in rotational form on the reference booklet, responses did not utilize this law to derive an expression for the tension in the string.<br>• Responses utilizing only Newton's second law in translational form frequently set the perpendicular component of the tension equal to the weight of the beam without considering the vertical component of the force of the hinge.<br>• Responses starting from Newton's second law utilized incorrect trigonometric functions when determining vector components of the tension force.<br>• Responses were not clear about substitution of provided variables ($L$, $M$) or left the expression for the tension force in terms of $F_g$. | • Responses demonstrating understanding utilized a derivation starting from Newton's second law in rotational form $\Sigma\tau = I\alpha$, chose the hinge as the axis of rotation, and set the net torque equal to zero $\Sigma\tau = 0$.<br>• Responses demonstrating understanding substituted correct expressions for the torque due to the gravitational force and the torque due to the tension in the string $(F_T \sin\theta)L = Mg\frac{L}{2}$ and then solved this equation for the tension. |

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|---|---|
| • About 30 percent of responses attempted to show functional dependence in part (c) but did not correctly relate the dependence to their response in part (b). | • Responses demonstrating understanding of how to use mathematical reasoning to justify a claim indicated the functional dependence between a decrease in the angle $\theta$ and the tension in the string, as well as relating that dependence to their reasoning stated in part (b). |
| • About 80 percent of responses drew a linear relationship representing a constant angular acceleration as the beam rotates. Very few responses showed a decrease in the angular acceleration with respect to time. | • Correct responses indicated that the angular speed increases and the rate of this change decreases with time, which shows an understanding that, as the beam pivots, the angular acceleration decreases as a result of the decreasing torque due to the gravitational force. |

***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?***

- The AP Physics 1 Workbook is a scaffolded collection of bite-sized practice pages. It helps students practice force diagrams and understanding Newton's second law in rotational form. The following pages would have been particularly useful in preparing students for this problem: 7B and 7E.
- 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.
- Practice drawing and labeling force diagrams where vectors are drawn as a distinct arrow starting on, and pointing away from, the point at which the force is exerted.
- Practice drawing and labeling force diagrams representing a system that is both in translational and rotational equilibrium.
- Practice drawing graphs where the relationship between the dependent and independent variables is nonlinear.

***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 AP Daily videos on translational and rotational equilibrium, as well as drawing force and free-body diagrams.
- Teachers should assign topic questions as well as personal progress check items to monitor progress being made in the mastery of content.
- Additional questions involving translational and rotational equilibrium can be found in the AP Physics 1 student workbook. These scenarios help students practice using free-body diagrams and force diagrams as well as Newton's second law in translational and rotational form to analyze scenarios of systems in equilibrium.

## Question 4

**Task:** Paragraph
**Topic:** Oscillations, Gravitation
**Max Score:** 7
**Mean Score:** 3.72

### *What were the responses to this question expected to demonstrate?*

The responses were expected to demonstrate the ability to:

- Explain how changing characteristics of a planet affect the gravitational force or acceleration near the planet's surface.
- Justify how work done by gravity will change if only the force of gravity changes in a scenario using the equation for work or the work-energy principle.
- Predict the effect of changing gravitational acceleration and pendulum length on the period of a pendulum.
- Predict the effect of changing force on the length of an elastic string.
- Construct a justification for why changing the gravitational force applied to an elastic pendulum could lead to an increase or a decrease in the period of the pendulum.

### *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 demonstrated mastery of the relationship between the mass and radius of a planet and the gravitational force/strength of gravitational field near the surface of a planet.
- Most responses used relevant equations and information from the prompt when attempting to justify why the work done on a pendulum would be different on different planets.
- A significant number of justifications for how changing gravitational force would lead to a change in work done on the pendulum did not mention both force and displacement or used insufficiently precise language to communicate all logical steps.
- Most responses displayed knowledge of the fact that an elastic string can stretch and related this to a possible change in the period of the pendulum. However, a significant number of these responses did not indicate a reason why length would change by different amounts in the two scenarios.
- Most responses included the equation for the period of a pendulum in their paragraph justification.
- Some responses incorrectly described how the period depends on the length and the value of $g$ ($T$ increases when $g$ increases, $T$ decreases when $L$ increases).
- Some responses addressed only the effect of changing $g$ or $L$, not both.
- Small number of responses incorrectly attempted to use the equation for the period of an oscillating mass on a spring to construct the justification for part (b).

***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 used "gravity" in their justifications instead of using the terms gravitational force, gravitational acceleration, or gravitational field, or the variables that represent those quantities.<br>• Responses justified claims about work done by gravity by referencing changes in force and not specifying gravitational force. | • Responses used precise language or symbols to clearly indicate that work done on a pendulum by a planet is dependent on the gravitational force exerted on the pendulum.<br>• Responses used precise language or symbols to clearly indicate that gravitational acceleration is inversely proportional to the period of a pendulum. |
| • Responses did not include the fact that vertical displacement remains the same for the pendulum in justifying why there is less work done on the pendulum by gravity on Planet X. | • Responses indicated that the work done on the second planet would be less because the gravitational force is less, and the vertical distance traveled is the same on both planets. |
| • Responses incorrectly attempted to use Work-Energy relation to justify why the work done by gravity will be less on Planet X by discussing only the initial gravitational potential energy on each planet. | • Responses related the *change* in gravitational potential energy to the work done and indicated that the change in gravitational potential energy will be less on Planet X. |
| • Responses did not discuss the reason that the elastic string would stretch more on the planet with more mass.<br>• Responses discussed the possibility that the string could be shorter *or* longer on the planet with more mass.<br>• Responses discussed the possibility that gravitational acceleration could be larger or smaller on the planet with more mass. | • Responses clearly linked the larger mass of the new planet to an increase in gravitational force or field strength on the pendulum and linked the larger gravitational force or field strength to a greater length of the string. |
| • Responses incorrectly used the relationship $g = \frac{F_g}{m}$ to argue that increasing the mass of a planet would decrease the gravitational acceleration near the surface of the planet. | • Responses used the equation $\lvert F_g \rvert = \frac{Gm_1m_2}{r^2}$ to determine the effect of changing the planetary mass on the gravitational force on an object. Then the response uses $a = \frac{\Sigma F}{m}$ to determine the effect on the gravitational acceleration. |
| • Responses incorrectly indicated that the mass of the sphere is different on planets with different mass. | • Responses indicated that the sphere has larger weight on the planet with larger mass and the same radius. |

***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?***

- The AP Physics 1 Workbook is a scaffolded collection of bite-sized practice pages. It helps students practice justifying claims with evidence as well as the concepts of simple harmonic motion and gravitation. The following pages would have been particularly useful in preparing students for this problem: 6D, 3N, and 3O.
- Assess students using the justify task verb as defined in the Physics 1 CED.

    - 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 the derived quantity.
    - Emphasize that this can only be predicted if one assumes that all other variables are constant.
    - Have students apply this type of reasoning to a scenario where students need to identify how variables will change and why.
- Remind students that when justifying claims with evidence, they need to identify which quantities are changing and which quantities remain the same.
- Stress that when making written arguments in physics, it is necessary to use precise terminology ($g$ or acceleration due to gravity vs. gravity) either with words or symbols.
    - It may be useful to have students practice with mathematical symbols and scientific terminology.
    - Try to use precise terminology when speaking about physics to students.

### ***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 AP Daily videos on simple harmonic motion, period of a pendulum, and gravitational force.
- Teachers should assign topic questions as well as personal progress check items to monitor progress being made in the mastery of content.
- Additional questions involving simple harmonic motion, the period of a pendulum, and gravitational force can be found in the AP Physics 1 student workbook. These scenarios help students practice using content to justify and support claims with evidence.

## Question 5

**Task:** Short Answer
**Topic:** Collisions
**Max Score:** 7
**Mean Score:** 2.96

### *What were the responses to this question expected to demonstrate?*

The responses were expected to demonstrate the ability to:

- Relate the change in kinetic energy of a stationary object to the final speed of the object.
- Recognize and apply the principle of conservation of momentum to both elastic and inelastic collisions.
- Relate the speed of an object with a position versus time graph.
- Recognize the behavior of the center of mass for a two-body system before and after collisions, and properly represent the center of mass speed on a position versus time graph after a collision.

### *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 (roughly 75 percent) were able to properly relate the change in kinetic energy to the final speed of Object B.
- About half of the responses began part (b) by recognizing that the position versus time plot of Object A after the collision would be a straight line with a positive slope reduced from the precollision slope.
- Approximately 70 percent of the responses recognized in part (b) that the position versus time plot of Object B would be a straight line with a positive slope.
- Approximately 50 percent of the responses recognized in part (b) that the center of mass position as a function of time maintained a constant slope for the entire time of $t = 0.0$ to $t = 2.0$ s .
- Approximately 35 percent of the responses were able to properly calculate the speeds of, and therefore the slopes of, Object A and Object B after the collision and represent the slopes on the position versus time graph.
- Approximately 25 percent of the responses correctly identified that the second scenario, of the blocks colliding and sticking together, was an inelastic collision. These responses indicated that the center of mass line for the inelastic case would be the same as the center of mass line for the elastic case, and then these responses provided a correct justification.

### *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 failed to connect the given information about the change in kinetic energy for Object B to finding the speed of Object B. | • Correct responses recognized that the change in kinetic energy could be used to calculate the speed of an object using $K = \frac{1}{2}mv^2$ . |

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| • Responses indicated that Object A stopped after the elastic collision (with a horizontal line on the graph) or that Object A moved to the left after the elastic collision (with a line with negative slope on the graph).<br>• Responses did not indicate the proper slopes for both Object A and Object B after the collision.<br>• Responses indicated that the center of mass line after the elastic collision had a different slope than it did before the collision. | • Responses properly used the information given and the conservation of momentum to calculate the speeds of Object A and Object B after the elastic collision. They then used this information to make lines on the graph for each object with the proper slopes.<br>• Responses recognized that the center of mass speed would remain the same as indicated on the prompt after the inelastic collision due to momentum conservation. |
| • When given the second scenario of the inelastic collision, responses indicated that the center of mass would remain constant and follow the same lines as Object A and Object B because the objects were stuck together. | • Responses addressed the prompt and indicated that the center of mass line from part (b) would not change with the new scenario because of momentum conservation in the isolated system. |

***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?***

- The AP Physics 1 Workbook is a scaffolded collection of bite-sized practice pages. It helps students practice sketching the motion of the center of mass of a system and using conservation of momentum and conservation of energy to describe collisions. The following pages would have been particularly useful in preparing students for this problem: 5M, 5N, and 5O.
- Use graphs to either pull information from or to give information about a situation. Discuss how the slope of a line could indicate a variety of information.
    - Students generally get a lot of practice reading graphs. They should also get practice constructing graphs in a variety of situations.
- Conservation of momentum in elastic and inelastic collisions should be covered and practiced thoroughly.
- The difference between elastic and inelastic collisions should be emphasized, as these words are used frequently on the AP Exam.
    - There are many simple lab activities to describe inelastic collisions where the objects stick together. Elastic collisions are a little harder, but simulations can be used to demonstrate the idea.
- The behavior of the center of mass of a system should be addressed.
    - There are video labs and online demonstrations that show the motion of the center of mass before and after a collision or explosion.
- Test-taking strategies should be reviewed. This includes things like using a ruler to draw straight lines, addressing the action verbs (determine, justify, etc.) used in exams, avoiding weaker wording like “it” in an answer, or being vague with wording. Answers should be definitive and should address what is being requested in the prompt.

***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 AP Daily videos on conservation of linear momentum, the motion of the center of mass of a system, and elastic vs. inelastic collisions.
- Teachers should assign topic questions as well as personal progress check items to monitor progress being made in the mastery of content.
- Additional questions involving conservation of momentum and collisions can be found in the AP Physics 1 student workbook. These scenarios help students practice using the ideas of conservation of momentum and re-expressing physical phenomena with graphs.