Chief Reader Report on Student Responses:

2023 AP® Physics 1: Algebra-Based Free-Response Questions

• Number of Students Scored	159,582		
• Number of Readers	624 (for all Physics exams)		
• Score Distribution	Exam Score	N	%At
	5	14,012	8.78
	4	29,244	18.33
	3	29,500	18.49
	2	44,620	27.96
	1	42,206	26.45
• Global Mean	2.55		

The following comments on the 2023 free-response questions for AP® Physics 1: Algebra-Based were written by the Chief Reader, Brian Utter, 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.

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Question 1

Task: Short Answer
Topic: Work and Energy in Simple Harmonic Motion
Max Score: 7
Mean Score: 2.90

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.
- Identify the relationship between period and frequency for oscillatory motion.
- Manipulate fundamental equations to apply to a specific situation.
- Apply the relationship between work and energy in a defined system.
- Graphically represent the relationship between the kinetic and potential energy in a defined system.

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

- The majority of the responses stated energy conservation as the reason that the x- and y-intercepts are the same for a graph of K vs. U for the cart-spring system. Incorrect responses used language that did not clearly communicate that the total mechanical energy is constant or described the functional dependence between K and U without stating the physics principle. A small number of incorrect responses cited Newton's laws or momentum conservation.
- Responses identified the correct equation for the period of a spring-mass oscillator and substituted a different mass when the block was dropped onto the cart, and most responses correctly substituted $4m$ for the new mass, though some responses incorrectly substituted $3m$ (the additional mass only). Common errors resulted from equating the expression for period from the equation sheet to the frequency without inverting the fraction. Most responses correctly constructed a ratio. Some responses correctly used proportional reasoning to describe the change in period when the mass increased by a factor of four, resulting in a frequency half as large.
- Very few students recognized that the reason the total energy remained the same after the block was dropped was that no work was done on the system by the block. The most common incorrect response for why the K versus U graph is unchanged after the block was dropped was that energy is conserved, which is a correct statement, but not an explanation as to why the additional mass does not change the energy of the system. Incorrect responses did not thoroughly uncouple kinetic energy from potential energy. Students did not recognize the importance of the block being dropped at the instant of maximum spring extension, as at that point, the two blocks have the same (zero) horizontal velocity.
- There was a large variety of x- and y-intercepts for the graph in part (c)(ii), when the students were asked to consider the system of only the cart and spring. Most of the responses correctly drew a single straight line. Many responses incorrectly traced over the original graph. A small number incorrectly drew the graph with maximum K and/or U greater than 4 J so that the new line was above the original line, indicating that the system gained energy.

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

<table>
<tr><th>Common Misconceptions/Knowledge Gaps</th><th>Responses that Demonstrate Understanding</th></tr>
<tr><td>

Responses demonstrated incomplete understanding of the law of conservation of energy.

Many responses equated kinetic and potential energy by stating that they are the same without indicating clearly when they are the same.
Sometimes Newton’s laws were used to explain why the x- and y-intercepts of the energy graphs were the same.

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Responses correctly applied conservation of energy.

$K = U_s$
No net external forces are applied to the system; therefore, no work is done on/by the system.

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Responses did not differentiate between period and frequency.
Some responses struggled with constructing a ratio.

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Responses correctly reasoned that a spring-mass oscillator with a mass of $4m_0$ will result in the period doubling compared to a system with a mass of m_0. Because frequency is the inverse of period, the frequency will be reduced to half the original value.
Responses correctly calculated the ratio by substitution into the equation for period of an oscillator:

$$\frac{f_2}{f_1} = \ldots \text{ or } \frac{T_1}{T_2} = \ldots$$
</td></tr>
<tr><td>

Some responses applied conservation of momentum when the mass was added.
Responses cited conservation of energy, stating that the total energy remained constant with no supporting reasoning that no net work was done or that there was no change to the spring potential energy when the mass is added.
Some responses attempt to apply gravitational potential energy.

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Responses correctly stated that no net work is done, or no net external force is being applied to the system, hence energy is conserved.
Responses correctly recognized that the system energy did not change because the block was dropped on the cart when the spring was at maximum extension, so there is no change to the spring’s potential energy.

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Responses graphed K vs. U for the spring-cart-block system when asked for the spring-cart system (no change from the original system graph).
Responses indicated a total energy greater than 4 J (energy was added to the system).

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Responses consisted of a graph showing that the newly defined system has less kinetic energy than the original system.
Responses included a sketch that remains below the graph for the original system, showing the new system has less K everywhere.

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• Responses had a maximum potential energy different from 4 J even though the spring did not change its maximum extension.	• Responses had the same x-intercept as the original system, showing the new system has the same $K = U$.

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?

- Emphasize the importance of clear, precise language in written responses. For example, when describing energy conservation, many responses stated that "the kinetic and potential energy are the same," which implies $K = U$, rather than $K + U = \text{constant}$.
- Remind students to read the prompt carefully and follow directions. The prompt instructed students to draw a line on the graph provided in Fig. 4. Many students drew a separate graph in the space beneath the prompt.
- Practice algebraic manipulation of equations for different task verbs:
  - **Derive** an equation—this means that the algebraic manipulation must start with a fundamental principle of physics or an equation on the equation sheet and must show multiple steps including appropriate substitutions.
  - **Determine** an expression—this is a single step manipulation that can be found by simple application of physics knowledge. "Determine" does not require work to be shown, only the final answer.
  - **Calculate** a numerical value—this means that the algebraic manipulation must start with a fundamental principle of physics or an equation on the equation sheet and must show multiple steps including appropriate substitutions. A question with the task verb "calculate" should include a final answer with units where appropriate.
- Explicitly teach students what constitutes a "physics principle."
- Practice algebraic manipulations with different operations:
  - Fractions with addition/subtraction, exponents, square roots.
- Spend time teaching the Work-Energy Principle
  - Work-Energy TIPERS are a good resource.
- Practice with different ways of visualizing the Law of Conservation of Energy:
  - Bar charts
  - K versus U graphs
  - K versus t graphs
  - U versus t graphs
  - K versus x graphs
  - U versus x graphs
- Practice redefining systems and representing the energy of those systems. For example:
  - Spring-cart → spring-cart-block
  - Ball-earth → ball
- Help students understand the relevance of each equation on the equation sheet.
  - Suggested activity: An AP FRQ situation is provided, and students are asked which equations are relevant/applicable.
- Advise students that because the exam is going to be scanned, they should not erase work but instead should cross out any work they do not want to be read and should write corrections in the additional space provided.

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 from Units 4 and 6 on Energy and Simple Harmonic Motion.
- Teachers should direct students to Higher Ed Faculty Lectures on Energy and Simple Harmonic Motion.
- 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 and Simple Harmonic Motion 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.

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Question 2

Task: Experimental Design
Topic: Kinematics
Max Score: 12
Mean Score: 5.00

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Identify a pair of variables (i.e., x vs. t^2) whose slope can be used with kinematics equations to determine the acceleration of the cart moving down a ramp.
- Apply an appropriate linear scale to the graph.
- Draw a reasonable best-fit line that follows the trend of the data points in the graph and that is not forced to go through data points or the origin.
- Use the slope of the best-fit line to calculate the acceleration of the cart down the ramp.
- Identify additional information needed to determine a relationship between g_{exp} and acceleration.
- Derive an equation to determine g_{exp} from acceleration.
- Identify a physical reason beyond friction and air resistance that would reduce g_{exp}.
- Develop arguments to justify a correct functional dependence between the physical reason and g_{exp}.
- Graph the position versus time and the velocity versus time for a cart going up a ramp.

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?

- Around a third of the responses demonstrated difficulty in the process of linearizing the x vs. t data.
- Some responses attempted to use variable relationships from kinematic equations but could not correctly linearize the data. For this response, there were a large variety of correct possibilities.
- About 80 percent of responses correctly identified quantities for part (a) that could be used to produce a linear graph whose slope could be used to determine acceleration.
- About eighty percent of responses had difficulty solving for correct acceleration from their linearized graph. Students who plotted average velocity (using change in position/change in time) vs. time had trouble relating their slope to the acceleration of the cart, forgetting to use kinematics and multiply the slope of their average velocity vs. time graph by two, or by using the mid-point of the time interval.
- Around three-quarters of responses for part (a) demonstrated key graphing skills, including the scaling of axes, plotting of data pairs, and drawing a line of best fit through the plotted data. About three out of four responses included correct best-fit lines while roughly two out of three were able to correctly plot data points on their graph.
- Around three-quarters of responses correctly calculated a slope using two points from their best-fit line.
- At least eighty percent of responses for part (b) correctly identified necessary additional measurements required to determine a value for g_{exp}.
- Half the responses demonstrated difficulty expressing g_{exp} in terms of "a" for part (b).
- In part (c), when presented with the idea that their experimental value for "g" was too low, many possible explanations were presented. About two of three responses were able to state at least one physical reason or a reasonable and specific measurement error that could significantly affect g_{exp} in a typical physics room.
- About one-quarter of responses focused on extraterrestrial labs or non-inertial reference frames as the reason, which were given credit, although that is not a reality for a student doing an experiment in their physics lab space. About one in six responses for part (c) were too general, referencing unspecified "human" errors or unidentified forces.

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- Showing a correct functional dependance between the physical factor identified in part (c) and a low value for $g_{\exp}$ was demonstrated by a small fraction of students. It was the most difficult section of the lab experiment question.
- About half the responses showed difficulty in interpreting the initial direction on kinematics graphs in part (d). There were many x vs. t and v vs. t pairs that were self-consistent but did not match the scenario.

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 response identifies $\frac{\Delta x}{\Delta t}$ as instantaneous velocity instead of average velocity causing responses to miscalculate the slope by a factor of two.	• Responses indicated correct slope analysis for average velocity vs. time. Assigning either in the initial set-up or after determining slope, a factor of two or other appropriate kinematics to determine acceleration.
• The responses identify the x vs. t plot, which is parabolic, as linear and force a best-fit line through zero.	• Responses indicated a variety of relationships, including $2x$ vs. t^2, which linearize the data and correctly used kinematic equations relating their slope to acceleration.
• The responses try to force the data to be linear using data points as the scale labels on the graph.	• Responses indicate a clear line of best fit and use appropriate scaling on the graph.
• The responses showed evidence of trying to use the measurement of height alone without any appropriate other measurements or set-up for calculating gravity from their ramp acceleration value.	• The responses found a variety of ways to determine the angle at the bottom of the ramp, as well as how to use height with energy calculations to determine $g_{\exp}$.
• The responses showed evidence of trigonometric confusion about which trigonometric function was appropriate for an indicated angle, such as $g_{\exp} = a \cos(\theta)$ using the angle to the horizontal angle.	• The responses showed understanding that an angle was needed or two measurements from the ramp were needed to determine the angle, then used appropriate trigonometry to solve for $g_{\exp} = \frac{a}{\sin(\theta)}$.
• The responses showed difficulty with listing one or more physical factors in the experiment that may have a significant effect on their $g_{\exp}$ value; some errors included irrelevant error in measuring mass or the effects of normal forces.	• The responses showed understanding that, for instance, the rotational inertia of the cart's wheels or measuring an angle greater than the actual angle measurements could have caused a low $g_{\exp}$ value.
• Responses often struggled to justify the functional dependence between a physical factor and $g_{\exp}$.	• The responses show understanding by discussing loss of energy to rotational motion reducing the translational motion and, therefore, the acceleration down the ramp.
• Responses had inconsistency between x vs. t or v vs. t kinematics graphs. Responses tended to either draw x vs. t or v vs. t correctly but incorrectly draw the	• The responses show understanding by correctly drawing appropriate curves for power or root functions for the x vs. t graph of an accelerating cart on a ramp

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other. Many had difficulty with direction and curvature of the kinematics graphs.	and the proper initial slopes $(+ / -)$ based on the initial velocity of the cart. The response shows a corresponding v vs. t graph, which matches the x vs. t graph.

What advice would you offer teachers to help them improve the student performance on the exam?

- Linearization of data should always start with an appropriate physics relationship, often an equation from the equation sheet. One process to encourage this would be to require that students follow a series of steps: 1. Copy a starting law or equation from the equation sheet; 2. Algebraically rearrange the equation to solve for the variable in question; 3. Assign the numerator to the y-axis and the denominator to the x-axis; 4. Calculate a new column of values for the data on each axis if needed; and 5. Determine what the slope would represent on your linearized graph.
- When calculating a slope, students should circle the points *on the best-fit line* that they intend to use in the calculation. Students should write the slope formula with the data points substituted in the appropriate locations and then write the numerical value of the slope with units.
- Students are expected to be able to compare values from graphs, calculate slopes, calculate areas, and then discuss the meaning of these calculations. To answer part (a) of this question, many responses calculated a slope, yet that slope was not the final answer. Students should be asked to interpret the meaning of slopes and areas of graphs with unfamiliar axes. An effective task is to show students a pair of axes and ask them to describe the significance of a single point, a calculated slope over a range, the instantaneous slope at a point, and the area under the graph within a range.
- Teachers should train students to replace the words "human error" in lab responses with a more specific error and/or physics explanation.
- It is important for teachers to craft their physics courses to allow students an opportunity to be frequently engaged in open inquiry lab experiences. Science practices 4 and 5 describe the skills students develop as they design, conduct, and analyze the results of an experiment.
- Unit 1 from the AP Physics 1 workbook would be a valuable resource, specifically page 1.L, which has the student work through a nearly identical linearization.

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 from Units 1 and 2 on Forces and Kinematics.
- Teachers should direct students to Higher Ed Faculty Lectures on Forces and Kinematics.
- 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 Forces and Kinematics 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.

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Question 3

Task: Qualitative-Quantitative Translation
Topic: Circular Motion
Max Score: 12
Mean Score: 5.02

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Identify a net force in a given scenario.
- Compare relative magnitudes of the net force in two different scenarios.
- Relate force and spring length through functional dependence.
- Relate force and tangential velocity in a circular motion through functional dependence.
- Compare tangential velocities in two scenarios based on centripetal force/acceleration.
- Derive an expression for tangential velocity beginning with Newton's second law equation.
- Identify the net force as a centripetal force.
- Identify the functional dependence between stretch length of a rotating spring and tangential velocity.
- Determine consistency between reasoning based on a conceptual argument and a derived equation.

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?

- About 40 percent of responses were able to identify the net force as the spring force, although the responses were not always explicit in specifically naming the spring force.
- About 80–90 percent of responses correctly related force and spring stretch length.
- Throughout the question 40 percent of responses generally were able to relate tangential speed and centripetal force to stretch length.
- About 70 percent of responses did a good job of connecting their qualitative responses to their derivations. Responses need to be specific about <u>how</u> the equation was used to determine the relationship.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
Part (a)(i)	
• Around a quarter of responses had the arrows pointing to the left but with correct lengths. • While the directions asked the student to draw the spring force, many drew multiple forces (ex. F_g, F_n, friction). If extra arrows were unlabeled it was impossible to determine which arrow represented the spring force.	• Correct responses showed the arrows pointing to the right to indicate that a centripetal force always points toward the center OR the arrows pointed towards the right because spring force is a restoring force. • Correct responses showed only one arrow per box to represent the spring force pointing toward the right.

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Part (a)(ii) • When explaining the arrow lengths that represent forces, a small fraction of responses assumed that the lengths of the arrows are actual stretch lengths; they did not connect the length to the force.	• Responses demonstrating knowledge of vectors (represented with both magnitude and direction) correctly drew spring force vectors (arrows), with both vectors to the right and longer at $t = t_2$.
Part (a)(iii) • Responses used the centripetal motion equation to compare speed but assumed that acceleration, or angular velocity, was constant. These responses usually indicated $v_1 > v_2$. Ex: $ma = mv^2/r$. "As r increases, v will decrease." • A small fraction of responses attempted to use conservation of energy to relate spring stretch distance to speed.	• Responses that demonstrated correct understanding chose the correct option $v_1 < v_2$ and justified the selection using a relationship between centripetal force and velocity. $F = mv^2 / r$.
Part (b)(i) • About half of responses interpreted the x in Hooke's law $(F = kx)$ as the total length of the spring $(L + d)$. • A small fraction of responses combined forces in both the horizontal and vertical directions when beginning the derivation leading to answers like $F_{net} = mg + kd$. The spring force is correct, but the response cannot earn credit for part (b)(i) because it doesn't recognize that the spring force is just kd .	• Responses indicated that x is the change in the length of the spring from its equilibrium length. • When beginning the derivation, responses stated $F_{net} = kx - kd$ and did not include F_g or F_n because the forces in the vertical direction are not relevant.
Part (b)(ii) • Of those responses that attempted this part, around half tried to use conservation of energy to relate spring stretch distance to speed. • A small fraction of responses attempted to use conservation of angular momentum as an argument because there are similar prompts in which a rotating object would decrease in angular velocity as the radial distance increases.	• Responses recognized that the two figures represent two distinct times in which the block-spring system is rotating. The transition between the two times (i.e., two different spring stretch lengths) occurred "behind the scenes" so that energy and/or angular momentum arguments were not sufficient (or even useful) in addressing the prompt. Correct responses recognized that applying Newton's second law with uniform circular motion was the correct approach.
Part (c) • About 80 percent of responses provided a functional dependence between velocity and stretch length but did not correctly relate it to either part (a) or part (b)(ii).	• Responses that showed both an understanding that as distance increased, velocity would also increase AND had an equation that supported the relationship demonstrated full understanding.

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

- Students have trouble beginning derivations and often did not even attempt to begin part (b) of the question.
  - In class, practice identifying which physics properties are being represented in specific scenarios through various diagrams or verbal descriptions. Then identify starting equations for that scenario. For example, a block is sliding down a ramp: Students should identify conservation of energy as the guiding principle, then write an equation $U_g = K$.
- An important part of making a proportional reasoning argument from an equation is to understand which variables remain constant in the scenario and which do not.
  - In the lab, or as part of an assessment, have students recognize what assumptions they are making. Not just what is negligible, but what is assumed to be constant, and if the assumption is reasonable. The "two student argument" type of question can be a good way for students to recognize this type of misunderstanding. Practice evaluating if an assumption is reasonable.
    - "Write an equation for the relationship between the falling time and the height," followed by, "What assumptions must be made to use that equation."
    - "Student A says the speed should be greater at $t = t_1$ because the radius is smaller, while student B says the speed should be greater at $t = t_2$ because the centripetal force is greater."
- Students do not know which spring equation is correct for forces, energy, or period. They mix them up and use them incorrectly.
  - Labs with multiple uses of springs can be incorporated. Complete a lab where the students must determine the spring constant more than one way (i.e., using period, using Hooke's law, etc.) AND calculate quantities within the lab for energy.
- Students struggle with springs in general because there are many different areas of the AP Physics 1 curriculum that involve springs: Forces and Motion, Energy, and Oscillations. The struggle tends to happen after all these areas have been covered but not connected.
- Ensure that springs are incorporated into each type of context so that students do not assume they know how to solve a problem that involves springs using only one method.
- Use images from released free-response problems and discuss the different approaches you could take in a scenario involving springs.
- Incorporate the AP Physics 1 Student workbook using Units 2, 4, and 6 to cover springs incorporating forces, energy, and simple harmonic motion.

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 from Units 2 and 3 on Forces and Circular Motion.
- Teachers should direct students to Higher Ed Faculty Lectures on Forces and Circular Motion.
- 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 Forces and Circular Motion 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 4

Task: Paragraph-Length Response
Topic: Torque and Rotational Motion
Max Score: 7
Mean Score: 2.56

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Determine an expression for the angular acceleration of a pulley using torque and rotational inertia.
- Describe torque applied to objects using force and lever arm.
- Compare changes in angular momentum for objects with different mass distributions.
- Indicate the relationship between mass distribution and rotational inertia.
- Compare angular kinematic quantities for objects with different rotational inertia.
- Explain how objects with the same change in angular momentum can have different changes in kinetic energy.
- Write logically, coherently, and concisely.

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 did well in recognizing that the torque on the disk in part (a) is based on the given force, F_T, while others incorrectly used the force of gravity on the hanging block as a starting point.
- Many responses used force, F_T, in place of torque in the expression and in the paragraph.
- Most responses did well in using the radius of the disk as the lever arm.
- Many responses successfully explained that the equal change in angular momentum is because the same torque is applied for the same elapsed time.
- Some responses incorrectly used conservation of angular momentum to explain the equal change in angular momentum for the disk and the hoop, despite the fact that the two systems are independent.
- Most responses did well in recognizing that disks and hoops differ in rotational inertia and relating that difference to rotational motion.
- Most responses did well in connecting change in angular velocity to rotational kinetic energy, but many did not explain that the angular velocity has a greater effect than the rotational inertia when they change by the same ratio because of the functional relationship $K_r = \frac{1}{2}I\omega^2$.
- Most responses were given as a logical, scientific argument, linking physics concepts together to address a question.
- Many responses did well in using given quantities to explain other quantities ("Since torque and time are the same, then change in angular momentum is the same."). Many others started from the given that angular momentum is the same, arguing that rotational inertia must be inversely proportional to angular velocity, making change in angular momentum the same. While this was helpful in explaining why rotational kinetic energy changed, it does not explain why angular momentum is the same.

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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 lever arm in the torque equation differs from the radius in general.	• The lever arm and radius are both represented by the R in this problem.
• The force on the pulley is the gravitational force on the hanging block.	• The force on the pulley is the tension in the string F_T.
• Two objects that don't interact can demonstrate conservation of momentum.	• The disk and the hoop each experienced the same torque for the same time, leading to the same change in angular momentum.
• Torque is another word for force used in rotational motion.	• Torque is force times lever arm. If the force and the lever arm are the same, torque will be the same.
• The center of mass of the disk is spread out, while the center of mass of the hoop is at the edges.	• The disk has more mass distributed near the center of mass, while the hoop has all mass far from the center of mass.
• A greater rotational inertia means an object is moving slower.	• The hoop resists change in rotation more than the disk due to a greater rotational inertia.
• Because rotational kinetic energy has rotational inertia in the equation, greater rotational inertia leads to greater rotational kinetic energy.	• The rotational kinetic energy expression contains rotational inertia and angular velocity. The angular velocity is squared, having a greater effect on rotational kinetic energy when the two quantities change by the same ratio.

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?

- When teaching conservation of angular momentum, teachers should emphasize situations in which conservation applies, i.e., systems with no external net torque. Conservation laws are generally used for interactions between objects within a system. Provide similar examples in which one case involves conservation while the other does not. Students often confuse conservation with same or equal in general. Teachers can point out that two quantities are often equal without there being any conservation laws involved.
- Be careful with comparisons of quantities between linear and angular paradigms. Avoid using phrases like "torque is a rotational force." Students can confuse analogous relationships for literal expressions. Provide multiple opportunities for students to translate between linear and angular quantities to develop familiarity.
- Students need to practice making logical arguments that flow from observed quantities to expected relationships. Students often use circular logic (for example, because change in angular momentum is the same, then rotational inertia times angular velocity must be the same, so that explains why change in angular momentum is the same). Stress for students to clearly identify what they "know" in a scenario and use that to determine other quantities.

- Clearly identify vocabulary and give the students the opportunity to practice using it correctly to avoid communicating misunderstandings in responses.

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 from Unit 7 on Rotation.
- Teachers should direct students to Higher Ed Faculty Lectures on Rotation.
- 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 Rotation 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.

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Question 5

Task: Short Answer
Topic: Torque and Energy
Max Score: 7
Mean Score: 1.57

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Relate the torque on a system to the force and angle at which the force is applied.
- Relate the energy of an object to the position or condition in a system.
- Derive an equation for the kinetic energy of a system using energy conservation.
- Describe how work can be done on a system by a force outside of the system and relate work to the energy change of the system.

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

- Correct responses identified Frame C as having the greatest angular acceleration and gave a brief explanation of the torque being greatest in that frame as justification. Incorrect responses failed to distinguish between force and torque, many times indicating incorrectly that Frame C had the greatest force exerted on it. Other incorrect responses indicated the torque was greatest but did not indicate the condition that caused the greatest torque at Frame C.
- Correct responses were able to identify Frame E as having the greatest rotational kinetic energy and gave a brief explanation using kinematics, torques, or conservation of energy as justification. Incorrect responses chose the wrong frame, often confusing largest velocity with the point of largest acceleration.
- Correct responses showed an understanding of energy conservation and of transformations from an internal force through a multi-step derivation starting from first principles. Incorrect responses typically did not show multiple steps in the derivation or began the derivation with an equation defining kinetic energy. Most commonly, incorrect answers failed to relate the change in gravitational potential energy to the difference in the position of the center of mass but instead used the total length of the object.
- Most students had problems articulating how changes to the boundary of the system affect how energy is transferred. Incorrect responses referred to the transfer of potential energy in the system and did not refer to work done by a force outside the system. Most incorrect responses did not indicate that the force of gravity is now outside of the system.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Force and torque are the same thing.	• For a constant force, the greatest torque occurs when the force is perpendicular to the radius vector.
• Velocity and acceleration are synonymous with each other.	• The greatest velocity occurs when the rod and sphere have accelerated downward for the longest amount of time.

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• When a derivation is asked for, only one line of work is shown.	• Complete derivations begin with fundamental principles or an equation from the equation sheet and then show substitutions from the list of variables appearing in the prompt. The derivation should be shown with each step on a new line as a multi-step process.
• The term "gravity" is synonymous with both force and acceleration.	• This object accelerates due to the force of gravity.
• Removing the Earth from the system is the same as removing the Earth from the situation (i.e., performing the experiment in space).	• If the Earth is not included in the system, it is now an outside force that will do work on the system, thus, changing the kinetic energy.

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 writing justifications using physics equations or concepts that are always true and applying these to the specific situation in the prompt. Responses need to justify each step of reasoning. Many times, the responses are too vague to receive credit or fail to directly connect changes in one variable to the effect on another.
    - Many good justification questions can be found in the AP 1 Workbook or in the TIPERs book.
- Teach students about systems with and without internal structure. A system with an internal structure can have internal energy. Forces from outside of the system can change the internal energy in the form of work.
- Use Energy Bar Diagrams to distinguish between internal and external forces and energy transformation.
- Have students work on evaluating the torque on the system when varying forces, angles, and location of force.
- Derived equations should always start with a law or equation from the equation sheet. When working on derivations, require that derivations contain at least three separate lines:
    1. A starting law or equation from the equation sheet.
    2. Explicit substitutions of variables and constants from the problem.
    3. The algebraically manipulated final expression.
- Students should practice deriving equations and be evaluated on the completeness of the derivation, in addition to the final result.
- Be specific with the physics vocabulary in class. Example: "Force of gravity" or "acceleration due to gravity" vs. "gravity."

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 from Units 7 and 4 on Rotation and Energy.
- Teachers should direct students to Higher Ed Faculty Lectures on Rotation and Energy.
- 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 Rotation and Energy 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.

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