Chief Reader Report on Student Responses:

2022 AP® Physics C: Mechanics Set 1 Free-Response Questions

• Number of Students Scored	46,301		
• Number of Readers	471 (for all Physics exams)		
• Score Distribution	Exam Score	N	%At
	5	12,222	26.4
	4	11,893	25.7
	3	9,867	21.3
	2	7,212	15.6
	1	5,107	11.0
• Global Mean	3.41		

The following comments on the 2022 free-response questions for AP® Physics C: Mechanics were written by the Chief Reader, Brian Utter, Teaching Professor, University of California, Merced. They give an overview of each free-response question and of how students performed on the question, including typical student errors. General comments regarding the skills and content that students frequently have the most problems with are included. Some suggestions for improving student preparation in these areas are also provided. Teachers are encouraged to attend a College Board workshop to learn strategies for improving student performance in specific areas.

© 2022 College Board.
Visit College Board on the web: collegeboard.org.

Question 1

Task: Short Answer
Topic: Newton's Laws of Motion
Max Score: 15
Mean Score: 7.25

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Draw free body diagrams indicating forces exerted on a system and the direction with appropriate labels.
- Determine an expression for an angle in terms of position. This requires the application of the geometric definitions of trigonometric functions and representing the angle in terms of the position for a moving object.
- Apply Newton's second law.
- Identify different types of forces, such as normal force, tension, gravitational force, and friction. Derive expressions for normal force and net horizontal force. This requires correct identification of the vector force components and representing those components in terms of the position of the object rather than the angle.
- Derive an expression for the work done by a varying force. This requires application of the integral definition of work and substituting/using the correct vector component.
- Correctly apply the dot product in a given scenario.

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 students did well drawing the free body force diagram of a string pulling a block across a table at an angle. Often, these were the only points earned. The most common mistake was to leave off the friction force.
- The question required the student to derive an expression for the angle as a function of position. Roughly half of the students did this correctly. Most who missed this tried to use a force equation to solve for the angle.
- Roughly half of the students correctly or partly correctly used Newton's second law in the vertical direction to derive an equation for the normal force as a function of position. Students most commonly did not start with a general statement of Newton's second law, instead skipping to a specific equation without showing the derivation from fundamental principles. A common mistake among students who did this incorrectly was using the forces in the horizontal direction and trying to solve for the normal force in the frictional force.
- The question required the student to express the net force in the horizontal direction as a function of position. Less than half of the students set up the sum of the forces correctly. Many didn't substitute into the equation correctly.
- Most students had difficulty setting up an integral that could be used to determine the work done by the tension in the string. Those who did set up an integral rarely used just the horizontal component of the tension and frequently were missing the limits of integration or the correct differential. The most common mistake among those who set up an integral was to integrate the entire sum of the forces in the horizontal direction. Those students with very high scores on this problem were most likely to miss points here.
- The question required the student to determine whether the work done by the string was greater in the first half of its motion or the second half of its motion and explain why. Not many students answered this completely correctly. Many that did answer the correct check box had incorrect or insufficient justifications. However, many of the correct justifications were stated quite well.

© 2022 College Board.
Visit College Board on the web: collegeboard.org.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Some students had difficulty with drawing and labeling free-body force diagrams.	• Each force on a diagram must touch and point away from the dot. Labels, rather than formulas, should be used.
• Many students misstated the formula for the friction force. Many used mg in place of the normal force.	• The friction force is equal to the coefficient of friction times the normal force, not the weight.
• Many students did not start with an expression of Newton's second law but rather skipped to a later starting point in their derivation or didn't carry out a derivation at all but just gave the final equation.	• In a question asking for a derivation, it is best to start with a general physical principle or equation from the formula sheet, for instance, Newton's second law, and then solve for the desired result in this specific scenario.
• Many students had difficulty setting up the integral. They frequently left off the limits of integration or the differential or used the wrong differential entirely (dt rather than dx).	• To calculate the work done by tension, it is necessary to integrate the dot product of the tension and dx. Because the box is sliding along the horizontal direction, the dot product necessitates using the horizontal component of the tension in the integral along with the appropriate limits of integration.
• Students had difficulty with the concept that as the angle of the string increased, the horizontal component of tension decreased, meaning that the work done by tension also decreased.	• The dot product between tension and dx means that only the component of tension along x does work. Because the horizontal component of tension is decreasing, the work done by tension is also decreasing.

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?

- On free body diagrams, use clearly defined labels; don't use formulas on the diagram.
- Teachers should emphasize clear, simple labels for the force arrows, consistent with standard examples in exam rubrics.
- Avoid drawing vectors and their components on the same free body diagram. For a free body diagram prompt, include individual forces and not the components.
- The most common error in (c)(i), (c)(ii), and (d) was failing to *derive* an expression. Many responses correctly stated the result, but a "derive" prompt requires a general starting point and steps or substitutions to reach the result. A single equation cannot earn full points for a derivation.
    - Teachers should model the process of derivation to show students the thinking process and the expectations of the exam.
    - Small-group activities in which students collectively discuss and complete a derivation can be helpful in building student confidence and understanding of the process of derivation.
- If you use acronyms that you have made up to help students remember something, remind them that someone reading their exam won't necessarily know what the acronym means, and they might lose points as a result.

© 2022 College Board.
Visit College Board on the web: collegeboard.org.

What resources would you recommend to teachers to better prepare their students for the content and skill(s) required on this question?

- Teachers can use AP Classroom to direct students to the AP Daily videos in the Forces and Energy units.
- Teachers can use AP Classroom to direct students to the Faculty Lectures on Forces and Energy.
- Teachers can assign topic questions and/or personal progress checks in AP Classroom to monitor student progress and identify areas for additional instruction or content and skill development.

© 2022 College Board.
Visit College Board on the web: collegeboard.org.

Question 2

Task: Experimental Design
Topic: Momentum and Collisions
Max Score: 15
Mean Score: 7.12

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

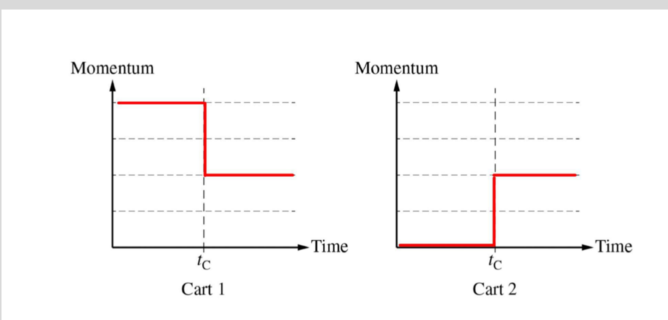
- Indicate that objects in an isolated system experience equal magnitude forces in opposite directions for the same period of time.
- Graph the individual momenta of two objects of different masses before and after an inelastic collision.
- Use conservation laws for energy and momentum to derive the speed of two objects after a collision.
- Draw a best-fit line when given a set of plotted data points.
- Calculate the slope of the best-fit line drawn.
- Relate the slope of a graph to a given equation.
- Analyze the functional dependence between two variables to determine how a change in one will affect the other.

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 students correctly identified that the impulses the carts applied to each other were equal; however, they could not correctly justify the selection using the definition of impulse as force times time.
- Most students recognized that the momentum of Cart 1 is increasing prior to the collision with Cart 2 and will be smaller in magnitude and constant after the collision.
- Most students also recognized that the changes in momenta for both carts are equal and opposite (Cart 1 loses while Cart 2 gains the same amount).
- Many students in part (c) correctly began the derivation with a statement of conservation of energy of the cart down the incline—gravitational potential energy converted to kinetic energy—in order to solve for the velocity of Cart 1 once it reaches the bottom of the incline and then correctly used a statement of conservation of momentum to then solve for the velocity of the two-cart system after the collision. Students who did not earn full points typically incorrectly applied energy conservation to this inelastic collision.
- Most responses clearly showed students know not to simply connect data points when drawing a line of best fit. However, there was a significant number of responses where students did connect the first and last data point or even began at the origin and drew a line to the last data point.
- Students clearly demonstrated their ability to calculate the slope of a line, but a large fraction of responses did not clearly nor correctly relate the slope to the mass of Cart 2 using the equation given in part (c).
- Students who were confident in analyzing functional dependence between two variables provided very clear and correct justifications in part (e).

© 2022 College Board.
Visit College Board on the web: collegeboard.org.

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

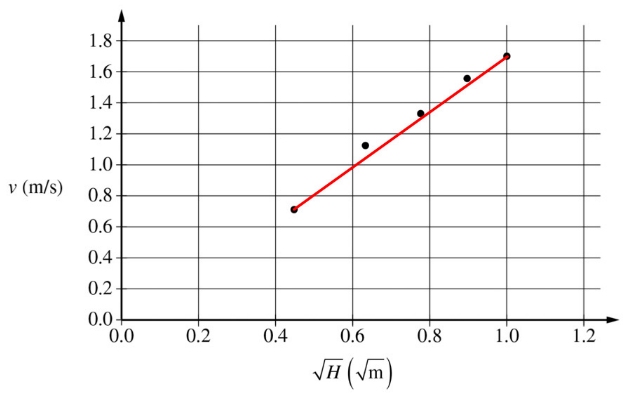
Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Responses confused impulse with momentum rather than a change in momentum and selected that the impulse on Cart 1 would be smaller due to a smaller mass. • Students sometimes did not fully justify the claim made, simply referring to Newton's third law and lacking the evidence that the time interval is equal during the collision as well as forces.	• Impulse is equal to the force times time, and because both carts apply equal forces on each other for equal amounts of time, the impulse applied is the same. • The forces between the carts were equal in magnitude by Newton's third law and the contact time was the same for each. • The net external force on the two-cart system is zero.
• Students often drew the initial and final momentum of the system as equal because the objects moved together after a perfectly inelastic collision, even though Cart 2 has a larger mass. • Students graphed the momentum of Cart 1 along the horizontal section prior to the collision, even though the prompt stated the collision occurred immediately after Cart 1 left the incline. Example: 	• Cart 1: Students should draw a straight line increasing to a maximum at the indicated collision time, t_c. The line should then drop to show Cart 1 decreases in momentum due to the collision. • Cart 2: Students should show a zero line up until the indicated collision time, t_c. The line should then rise to a constant value that is higher than the line drawn for Cart 1. The graph had to demonstrate an understanding of conservation of momentum by reflecting equal and opposite changes in the momentum of the carts.
• Students incorrectly combined energy and momentum terms into a single expression: $m_1 gh = \frac{1}{2}(m_1 + m_2)v_1^2$ • Students jumped to the equation $v = \sqrt{2gh}$ without showing any supporting work.	• $m_1 gh = \frac{1}{2} m_1 v_1^2$ $v_1 = \sqrt{2gh}$ $m_1 v_1 = (m_1 + m_2) v_f$ $m_1\left(\sqrt{2gh}\right) = (m_1 + m_2) v_f$ $v_f = \sqrt{2g}\left(\frac{m_1}{m_1 + m_2}\right)\sqrt{h}$

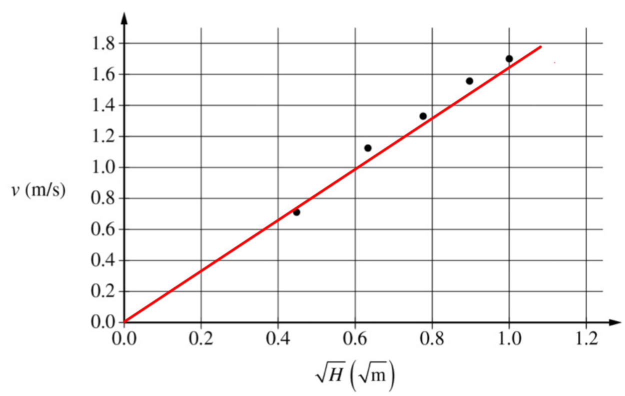
© 2022 College Board.
Visit College Board on the web: collegeboard.org.

<table>
<tr>
<td>

- Students incorrectly drew lines of best fit, having significantly more data above or below the line. Other incorrect drawings included: a curve forced to hit the data points, a line beginning at the origin, or a line connecting the first and last dots.

Examples:





</td>
<td>

- Students should use a straightedge to draw a line that splits the middle of the points, with a balance of points above and below the line. The line must show the general trend of the data and must not assume that the line must go through the origin.

</td>
</tr>
<tr>
<td>

- Students used data that was not on their line of best fit to calculate a slope or did not clearly show what data was used to do the calculation.
- Students plugged in a single data point to the equation for the line, which is inaccurate if the line did not pass through the origin.

</td>
<td>

- Students should have chosen points from a best-fit line to determine the slope of a graph, clearly writing out the calculation and ideally circling those points used on the graph.
- Clearly identify the slope and its relationship to m_2:

$$\text{slope} = \frac{v}{H} = \sqrt{2g}\left(\frac{m_1}{m_1 + m_2}\right)$$

</td>
</tr>
</table>

© 2022 College Board.
Visit College Board on the web: collegeboard.org.

• Students who did not use the equation from part (d) had a hard time adequately justifying the connection between the masses during the collision: students referred to human error or equipment failure. • Students simply plugged smaller values into the equation and stated the mass must be smaller; however, they did not adequately justify the relationship.	• Students should have identified that the slope of the data $\frac{v}{H}$, remains constant. Then referenced the equation given, $\frac{v}{H} = \sqrt{2g}\left(\frac{m_1}{m_1 + m_2}\right)$ indicating that as m_2 decreases in the denominator, m_1 must decrease as well. • Another acceptable response: Per the equation derived in part (d) and everything else remaining constant, m_1 is directly proportional to m_2 and if m_2 decreases, m_1 must decrease for the equation to be valid.

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?

- Remind students they can bring a straightedge or ruler to the exam.
- Provide opportunities for students to use Claim-Evidence-Reasoning in the classroom to practice clearly justifying their answers to questions.
- Practice justification and reasoning skills with students. What makes a response a valid and adequate justification is hard to explain but easier to model and practice.
    - Using ranking tasks in the classroom can inspire students to convince other classmates of their choices using solid reasoning to support their claims.
- Have students practice questions that incorporate the use of conservation of energy and conservation of momentum in the same question. This will allow students to develop their skills and recognize scenarios where the use of conservation of energy and conservation of momentum are appropriate. There are online simulations for collisions where great inquiry-based questions can be explored.
- Students should graph data by hand, draw best-fit lines, and calculate slopes for experiments done in class. Students need to practice drawing lines of best fit based on scattered data. Remind students that not all lines go through the origin.
    - Use similar graph styles and scales to those found on AP Exams to increase familiarity with the style.
- Students need to clearly show their steps in a derivation, i.e., no skipping of steps. This is also true for prompts that ask students to calculate values. Students must show where the values are coming from and how they are being used in their work in order to earn full credit.

What resources would you recommend to teachers to better prepare their students for the content and skill(s) required on this question?

- Teachers can use AP Classroom to direct students to the AP Daily videos in the Energy and Momentum units.
- Teachers can use AP Classroom to direct students to the Faculty Lectures on Energy and Momentum.
- Teachers can assign topic questions and/or personal progress checks in AP Classroom to monitor student progress and identify areas for additional instruction or content and skill development.

© 2022 College Board.
Visit College Board on the web: collegeboard.org.

Question 3

Task: Short Answer
Topic: Rotation
Max Score: 15
Mean Score: 5.50

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Read, analyze, and correctly interpret the statement of a prompt, including diagrams showing the apparatus at different moments in the described scenario.
- Apply the concept of both translational and rotational equilibrium.
- Draw forces on a rigid body diagram in the correct location and correct orientation.
- Apply symbolic expressions and algebra to determine the correct relationship between variables within an equation.
- Sketch a graph that shows a functional relationship between angular velocity and time after determining the relationship between angular acceleration and angular position.
- Apply the concept of rotational equilibrium to determine the change in the magnitude of each torque on the rigid body if the axis of rotation changes from its original location.

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 students understood that for this apparatus, equilibrium could use either the fact that the sum of the torques equals zero or that the sum of the forces equals zero. A significant majority used the fact that the sum of the forces equals zero.
- Some students struggled to correctly relate the stretch of the spring connected to the string to the arc length of the rotation of point *P*.
- Some students incorrectly attempted to apply conservation of energy to the stretching of the spring and lowering of the block. The prompt states, "the block is slowly lowered until the spring-disk-block system reaches equilibrium," which indicates the presence of an external force doing work on the system.
- Most students correctly applied the force due to gravity at the center of mass of the disk, directed downward.
- Most students understood that the tension in the string attached to the spring was exerted tangent to the disk toward the spring.
- Some students did not realize when drawing the force due to the axle that it would need to be placed at the center of mass and oriented so that the sum of the forces was zero in both the horizontal and vertical directions.
- Many students understood the net torque on the disk resulted in an angular acceleration of the disk once the string attached to the block was cut. Some students did not realize the tension in the string that applied a counterclockwise torque was due to the spring to which the string was attached.
- Some students incorrectly attempted to solve for angular acceleration via rotational kinematics. The response attempt was typically abandoned quickly, given the number of terms that did not correspond to stated acceptable terms in the answers.
- Many students made little to no attempt to respond to the second derivation prompt.
- Some students did not attempt the sketch of a graph portion of the prompt.
- Many students recognized the angular velocity would start at zero and continually increase until time t_1. Some students sketched a linear angular-velocity time relationship, not recognizing the relationship between the decreasing torque and how it would appear on a graph of angular velocity as a function of time.
- Some students had difficulty clearly expressing the change in a torque due to a force. The structures of the responses indicated the force changing rather than the torque changing.

© 2022 College Board.
Visit College Board on the web: collegeboard.org.

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>

Students did not apply that "equilibrium" means linear and angular acceleration equal zero by not substituting for linear or angular acceleration (i.e., application of $\Sigma\tau = I\alpha$ or $\Sigma F = ma$).
Students confused $\frac{1}{2}k(\Delta x)^2$ and $k\Delta x$ when substituting into $\Sigma F = 0$.
Students did not recognize the stretch of the spring was equal to the arc length through which point P rotated.
Students did not realize that "slowly lowered" means an external force does work, which results in mechanical energy not being conserved.

</td><td>

$\Sigma\tau = 0$ or $\Sigma F = 0$
$\Sigma F = 0 = m_B g - k\Delta x$
$\Delta x = \theta R$
$\Sigma\tau = 0$ or $\Sigma F = 0$
$\Sigma\tau = 0 = \tau_{\text{weight of block}} - \tau_{\text{tension due to spring}}$ OR
$\Sigma F = 0 = F_{\text{weight of block}} - F_{\text{tension due to spring}}$

</td></tr>
<tr><td>

Students did not make a distinction between torque and forces. They related $I\alpha$ simply to force rather than $\vec{R} \times \vec{F}$.
Students would sometimes use terms not defined in the rigid body diagram or the prompt, which were not descriptive enough to demonstrate understanding that the tension in the string was due to the spring.

</td><td>

$\tau_{net} = I\alpha = \tau_{\text{tension}} = F_{\text{spring}} R$

</td></tr>
<tr><td>

Students did not clearly indicate the change stated was due to a torque caused by a specific force, rather a vague statement of "the force" or "that force."
Students did not apply the concept of rotational equilibrium would mean the sum of the torques continues to be zero, even if the lever arm is changed.

</td><td>

Torque due to the force of gravity on the disk would increase.
Torque due to the tension caused by the weight of the block would increase.
Torque due to the tension caused by the spring would increase.

</td></tr>
</table>

© 2022 College Board.
Visit College Board on the web: collegeboard.org.

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?

- The most successful derivations begin at fundamental principles. It was common to see an answer begin several steps into the derivation process with an incorrect expression, likely the result of an incorrect substitution whose step was not shown.
  - Have students practice deriving expressions in pairs or small groups. They should define any terms not given in the prompt. Have them present the derivation, and if anyone asks where a term or expression comes from, the presenters should explain the thought process again, looking for steps that weren't written down.
  - While not required, stating the expression for the term to be substituted to the side of the derivation can help the student be clear about their intention.
- Students are aware that units are an important part of a numeric answer and were including them inappropriately in variable-only answers. The symbolic expressions show the relationship between variables. The final units of a numeric answer depend on the units of the substituted values. Unit conversions are needed for the numeric substitutions, not the development of the relationship between two quantities. From the responses, it was clear students understood the relationship $\text{arc length} = \theta R$ is only valid if θ is in radians. Any conversion between degrees and radians should happen when substituting values, not in the derivation of the relationship. Additionally, there should not be an algebraic expression followed by a set of units.
- When indicating the change in torque caused by a specific force when the placement of the axes of rotation changed, it was difficult for students to clearly express what changed (the force or the torque) and in which way. This is a place where using a chart to organize information would prove helpful. When answering questions, students should be encouraged to organize answers to make them accessible to someone reading the work. This could be a clear opening or final statement in an answer area or using a table like the one below:

Force	*Change in the exerted torque relative to part (b)*
Force of gravity on disk	Increased
Force of tension due to block	Increased
Force of tension connected to spring	increased

What resources would you recommend to teachers to better prepare their students for the content and skill(s) required on this question?

- Teachers can use AP Classroom to direct students to the AP Daily videos in the Rotation unit.
- Teachers can use AP Classroom to direct students to the Faculty Lectures on Rotation.
- Teachers can assign topic questions and/or personal progress checks in AP Classroom to monitor student progress and identify areas for additional instruction or content and skill development.

© 2022 College Board.
Visit College Board on the web: collegeboard.org.