Chief Reader Report on Student Responses:

2024 AP® Physics C: Mechanics Set 1

Free-Response Questions

• Number of Students Scored	61,252		
• Number of Readers	685 (for all Physics exams)		
• Score Distribution	Exam Score	N	%At
	5	17,464	28.5
	4	16,444	26.8
	3	12,822	20.9
	2	8,098	13.2
	1	6,424	10.5
• Global Mean	3.50		

The following comments on the 2024 free-response questions for AP® Physics C: Mechanics 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.

Question 1

Task: Mathematical Derivation and Graphical Analysis
Topic: Conservation Laws and Oscillations
Max Score: 15
Mean Score: 8.05

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Derive an expression using conservation of mechanical energy between spring potential energy and kinetic energy.
- Determine the work done on an object by the force of friction.
- Apply conservation of linear momentum during a collision.
- Analyze and interpret a graphical representation of kinetic energy as a function of time.
- Describe the change in kinetic energy in scenarios of both constant and variable forces.
- Determine the relationship between the length of a pendulum and its frequency of oscillation.

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 used conservation of energy to show that as the block experienced a force from the spring, the spring potential energy of the block-spring system decreased as the kinetic energy of the block increased. Some responses did not use the proper subscripts for the spring compression, so it was unclear which distance was being considered in the calculation.
- Most responses attempted to find the speed after the region of nonnegligible friction by using the work-energy theorem. Some responses incorrectly considered the final kinetic energy after the collision rather than before.
- Most responses subtracted the energy dissipated by friction from the initial energy, although some responses incorrectly subtracted the force of friction instead. There were a variety of algebraic errors when calculating the final energy.
- Many responses correctly found the speed after the region of nonnegligible friction by using a force and kinematics approach. Some responses applied the incorrect sign of the acceleration, which incorrectly led to an increase in the block's speed, rather than a decrease.
- Most responses used conservation of linear momentum to find the speed of the two-block system after the collision. Responses that did not determine a speed at x_2 were unable to successfully substitute a speed into the equation.
- Most responses did not draw a correct function during the time interval $0 \le t \le t_1$. Because the block is in simple harmonic motion, its position function is of the form $x(t) = A\cos(\omega t)$ which produces a velocity function of the form $v(t) = -A\omega\sin(\omega t)$. This results in a sinusoidal function drawn for $0 \le t \le t_1$.
- The kinetic energy should be proportional to the velocity squared, yielding a function that starts at zero, gradually increases in slope, and then gradually decreases in slope. However, most responses recognized that the kinetic energy increases at a nonlinear rate, which was sufficient to earn a point in this section.
- Most responses sketched a linear function, rather than one with a decreasing slope, during the time interval $t_1 \le t \le t_2$.
- Most responses correctly drew a horizontal line during the time interval $t_2 \le t \le t_3$ because no work was done on the block.

- Most responses accurately described the kinetic energy changes during the time interval $0 \le t \le t_1$ consistent with their graph. Responses that considered the spring to be part of a block-spring system discussed the conversion of spring potential energy into kinetic energy, while responses that considered a system of the block alone discussed the spring as providing an outside force that does work on the block. Few responses successfully explained why the graph should be nonlinear, either by recognizing that work is not done at a constant rate or that the force is not applied at a constant rate.
- Some responses also discussed the graph beyond the time interval stated in the question. While these additional explanations were not considered during scoring, the time spent in writing these explanations could have been spent more effectively elsewhere.
- Most responses were able to identify a decrease in the frequency of oscillation as the pendulum was lengthened. The responses were split between explanations that first discussed a change in the pendulum period and responses that immediately discussed frequency. Some responses attempted to justify an answer by merely repeating the prompt statement and their selection.

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 incorrectly assumed that kinetic energy is conserved in an inelastic collision and applied this assumption by equating the initial energy to the kinetic energy after the collision.	• Responses correctly derived the speed at x_2 by using the work-energy theorem, and then solved for the final speed by using conservation of linear momentum.
• Responses failed to indicate a negative value for the acceleration when deriving an expression for the speed at x_2.	• Responses included a minus sign in the acceleration term when calculating the speed at x_2.
• Responses incorrectly sketched a graph that is linear for the time interval $0 \le t \le t_1$.	• Responses sketched a graph that has a sinusoidal shape for the time interval $0 \le t \le t_1$ because the block is in simple harmonic motion.
• Responses incorrectly sketched a graph that is linear for the time interval $t_1 \le t \le t_2$. This could result from drawing a graph of kinetic energy as a function of position rather than as a function of time.	• Responses recognized that the kinetic energy will be reduced by the same amount for each constant unit of distance traveled. Because the distance and t_2 are not linearly proportional, the graph will have a large slope at the beginning of the time interval, but this slope will gradually decrease.
• Responses included a justification for the nonlinear graph by referring to the quadratic nature of the equations for spring potential energy and kinetic energy.	• Responses included an explanation that referenced a quantity that changes over time, such as the work done by the spring, or the force applied by the spring.
• Responses failed to distinguish between the period of a pendulum and the frequency of its oscillation.	• Responses clearly indicated that the period and frequency are inversely related.

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?

- When there are more than two relevant locations or times within a question, the response should be extremely clear which two locations or times are being compared. Use of subscripts is an effective way to make these distinctions.
- When producing a graph, it is important to double check the variable on the vertical and horizontal axis to ensure that the correct variables are being considered.
- Read the prompt and question carefully and only answer the question being asked.
- If a question involves a checkbox, the explanation should provide more information than simply restating the given information and the selection made.
- Emphasize that when asked to derive an equation, the responses should start with an equation from the equation sheet or a fundamental physics principle (e.g., conservation of energy) and should have multiple steps.

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

- Teachers should direct students to the AP Daily Videos on conservation of 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.

Question 2

Task: Experimental Design
Topic: Resistive Forces Dynamics
Max Score: 15
Mean Score: 9.59

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Determine the relationship between variables by deriving a differential equation applying Newton's second law to a falling object experiencing a drag force.
- Select relevant features on a velocity-time graph by recognizing when equilibrium occurs.
- Support a claim with evidence from experimental data by recognizing an object in equilibrium indicates that the sum of forces exerted on the object is equal to zero.
- Determine a line of best fit for given data.
- Explain how the graph illustrates a physics principle by calculating slope for a linear function and using this to calculate an unknown drag constant.
- Explain how the initial velocity given to an object influences the drag force.
- Describe how to determine the functional dependency between two variables in an experiment.

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 recognized that Newton's second law was required to derive an expression for speed.
- Most responses recognized that a derivation required more than one step.
- Most responses were able to correctly write a differential equation.
- Most responses recognized that when a velocity-time graph has a slope of zero, the sum of the forces is zero or that the system is in equilibrium.
- Most responses could draw a line of best fit.
- Most responses could calculate an appropriate slope from the line of best fit.
- Some responses did not make the connection between the slope of the graph and the equilibrium equation that would exist if the falling object had reached a terminal velocity.
- Some responses were not able to explain how throwing an object upwards would not change the terminal velocity as the object falls.
- Most responses were able to describe how they would utilize a graph to investigate a 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*
• Responses equated a constant slope to a zero slope.	• Responses indicated that a constant value graphed indicates that the slope of the line is zero.
• Responses indicated that the slope of the graph was equal to the value of b or the drag constant. • Responses equated the y-intercept of the graph to the value of b or the drag constant.	• Responses related the value of b to g and divided by the slope.
• Responses applied conservation of energy to a scenario with a nonconservative force (drag).	• Responses analyzed results in terms of net forces.
• Responses did not connect a slope of zero on a velocity-time graph to the object being in equilibrium or to the sum of the forces being equal to zero.	• Responses correctly interpreted that a zero slope on a velocity-time graph indicates that the sum of the forces is equal to zero.
• Responses incorrectly applied kinematic equations for constant acceleration.	• Responses included analyses based on nonuniform acceleration.
• Responses equated the maximum velocity of a falling object to terminal velocity.	• Responses indicated that not all objects that fall will reach terminal velocity.

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?

- When teaching graphical analysis, have students describe in words what their graphs represent.
    - TIP: Students should understand the reason for making a graph and how their data connects to theory.
- If a student can see that a velocity-time graph has a region of zero slope, they should be able to say that an object is not accelerating and that the object is in equilibrium. They should also be able to connect the idea of "equilibrium" to the sum of all the forces exerted on an object being equal to zero.
- When teaching dynamics, include forces that vary depending on speed and displacement.
    - TIP: Include variable force situations (e.g., drag and spring forces) in your teaching.
- Introduce the concept that not all forces are constant throughout a problem. This can make it easier for students to look for conditions where forces are not constant.
- If students do not have a strong background in calculus, a good introduction is to have them set up the differential equation without solving the equation.
    - TIP: Work out example problems in the classroom where air resistance is not neglected. Model air resistance as a linear or quadratic function of the speed and use Newton's second law to set up a differential equation instead of an algebraic equation.

- Emphasize that when asked to derive an equation, the responses should start with an equation from the equation sheet or a fundamental physics principle (e.g., conservation of energy) and should have multiple steps.
    - TIP: Have students work on group assignments and in-class activities where students model physical systems and derive expressions for velocity or position as functions of time. Provide standard equation sheets so students can get started from simple equations, but the students must realize that these simple equations are inadequate to accurately describe the motion of real-world objects.

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 resistive forces and Newton’s second law.
- Teachers should utilize the question banks to find items that assess similar content and skills and create practice assignments for students.
- Teachers should direct students to topic questions as well as personal progress check items to monitor progress being made in the mastery of content.

Question 3

Task: Mathematical Derivation and Calculus Applications
Topic: Torque, Rotational Statics, and Rotational Dynamics
Max Score: 15
Mean Score: 4.93

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Draw and label force vectors on a rigid body diagram.
- Determine the magnitude of a torque associated with a force exerted on a rigid body.
- Determine the magnitude of torque exerted on a rigid body due to the gravitational force.
- Derive an unknown force exerted on a rigid body that is in a state of translational and rotational equilibrium.
- Demonstrate a conceptual understanding of the relationship between the torque provided by a force and the angle at which the force is exerted.
- Calculate the mass of a thin rod of nonuniform density based on the linear mass density of the rod.
- Calculate the moment of inertia of a thin rod of nonuniform density.
- Determine the differential mass dm in terms of x from the linear mass density of the rod.

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 draw and label appropriate forces on the diagram.
- Many responses did not include a pivot force. Responses that did include the pivot force drew it correctly pointed up and to the right.
- Some responses incorrectly included extraneous forces on the diagram. The most common extraneous forces included were various gravitational forces instead of including a gravitational force only at the center of mass of the rod.
- Most responses correctly stated that the sum of torques had to be zero, or that clockwise and counterclockwise torques were set equal, to indicate equilibrium.
- Most responses included a term for each force exerting a torque about the pivot point. Some responses included $\sin(\theta)$, instead of $\sin(90° - \theta)$ or $\cos(\theta)$, for the torque exerted by the tension force.
- Most responses indicated that the tension in the string would decrease.
- Many responses referenced their final equation from part (b) in the justification for part (c). However, this equation no longer applies because the angle between the rod and the string is no longer $90° - \theta$.
- Most responses correctly started with an integral to calculate the mass of a rod with variable mass density. However, many responses did not distribute dx through both terms of λ.
- Some responses correctly started with an integral rotational inertia equation. A common confusion was failing to replace r^2 with x^2, which made it difficult for the student to integrate correctly.
- Many responses attempted to derive the rotational inertia with non-integral versions of the parallel axis theorem.
- Many responses began with intermediate steps. Derivations should begin with an equation from the equation sheet or a fundamental physics principle and show intermediate steps.

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 omitted the force exerted at the pivot point.	• Responses included all relevant forces on the diagram and labeled them with distinct labels for each force.
• Responses used identical labels for different forces (such as F_g and F_g).	• Responses included similar labels for similar forces with more specific names to clarify differences, e.g., $F_{g,\text{rod}}$ and $F_{g,\text{block}}$.
• Responses included extraneous forces exerted on the rod.	• Responses included only the correct vectors for the forces: the pivot force at the pivot; only the force due to the hanging mass at Point P; only the gravitational force at Point C; only the tension force at Point Q.
• Responses included vector components instead of the vector.	• Responses included the appropriate vector arrows, not components, as indicated in the prompt.
• Responses had the pivot force vector drawn vertical or drawn horizontal.	• Responses applied a conceptual understanding of net forces to recognize that the pivot force vector should be drawn up and to the right.
• Responses often did not recognize that the angle between the tension and the radius was different from the angle θ given in the problem.	• Responses substituted $\sin(90° - \theta)$ or $\cos(\theta)$ in the expression for torque due to the tension on the rod.
• Responses often did not provide a complete justification explaining why the tension decreases.	• Responses indicated that the tension in the string decreases because the angle between the rod and the tension becomes closer to 90°, so less tension will be needed to provide the same torque.
• Responses indicated that the string was longer and, therefore, would provide more torque.	• Responses related the angle between the string and the rod to the torque.
• Responses multiplied the linear mass density by x to determine the differential mass when calculating the mass of the rod, e.g., $\int \lambda x \cdot dx$.	• Responses correctly replaced the differential mass with the linear mass density and integrated, e.g., $\int \lambda \cdot dx$.
• Responses did not indicate that $r = x$ and that $dm = \lambda dr$ in the integral for rotational inertia.	• Responses correctly integrated $\int_0^{1.2\text{ m}} (6 + 10x)\,dx$.
• Responses did not include units for numerical answers.	• Responses included proper units on all numerical answers.

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?

- Make sure that students read the instructions and draw vectors (not components) on force diagrams.
- Have students practice generating logical labels for forces especially when there are two forces with similar titles, such as T_1 and T_2.
- On parts that require answers in words, have students practice stating the obvious. For example, the torque must remain the same; therefore, the tension must decrease.
- Ensure students make proper substitutions in their integration equation, including replacing "default" variables with those given in the prompt, e.g., replacing r with x.
- Emphasize that when asked to derive an equation, the responses should start with an equation from the equation sheet or a fundamental physics principle (e.g., conservation of energy) and should have multiple steps.
- Encourage students to avoid starting with fully arithmetic statements. Most arithmetic must be supported with accepted physics or mathematical concepts.

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

- Teachers should direct students to the AP Daily Videos on torque, rotational statics, and rotational dynamics.
- Teachers should assign topic questions as well as personal progress check items to monitor progress being made in the mastery of content.