Chief Reader Report on Student Responses:

2024 AP® Physics C: Mechanics Set 2

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, Impulse, and Simple Harmonic Motion
Max Score: 15
Mean Score: 7.73

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 energy, including energy dissipated by friction.
- Apply conservation of momentum during a collision.
- Analyze and interpret a graphical representation of momentum as a function of time.
- Identify patterns on a momentum-time graph using force principles.
- Identify factors that affect the period of an oscillating spring system.

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 as the block traveled down the incline plane. Some responses included the energy dissipated due to friction on the incline plane.
- Most responses used conservation of momentum to find the velocity of the blocks after the collision.
- Most responses used the conservation of energy for the moving blocks compressing the spring to derive the spring constant.
- Most responses sketched a graph that showed an increase in momentum as the block traveled down the inclined plane during the time interval $0 \le t \le t_1$.
- Most responses sketched a graph that had constant momentum as the block traveled on the level surface during the time interval $t_1 \le t \le t_2$.
- Some of the responses sketched a graph during the time interval $t_2 \le t \le t_3$ that had a lower constant momentum after blocks A and B collided.
- Most responses did not sketch a graph that was a decreasing linear line instead of a concave down curve during the time interval $t_3 \le t \le t_4$.
- Most responses identified that the blocks decreased in momentum or velocity when hitting the spring.
- Some responses connected the decrease in momentum to the opposing spring force.
- The most challenging pattern to identify was that the opposing spring force continued to increase, which led to a larger and larger decrease in momentum.
- Most responses identified that the mass and spring constant were not changed in the new procedure and that this caused the period to remain the same.
- Many responses justified the period not changing by identifying that the new increased velocity, spring compression, or amplitude did not change the period of the spring-block oscillator by looking at the equation.

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 did not include the energy dissipated by friction as the block traveled down the inclined plane.	• Responses included the mechanical energy dissipated by friction as the block traveled down the inclined plane.
• Responses incorrectly solved for the new velocity of the two-block system after the inelastic collision for the horizontal portion of the track where friction was nonnegligible.	• Responses correctly solved for the new velocity of the two-block system using conservation of momentum.
• Responses did not indicate that the momentum of Block A decreased due to the reduced velocity after the collision at t_2, even though momentum is conserved.	• Responses sketched a constant momentum with a lesser value on the graph during the interval $t_2 \le t \le t_3$ than during the interval $t_1 \le t \le t_2$.
• Responses incorrectly applied a non-linear spring force.	• Responses sketched a concave down curve during the interval $t_3 \le t \le t_4$.
• Responses failed to state that the two-block system slowed down due to an opposing force or acceleration. Instead, responses included an equation for the spring force with a statement about the increased spring compression distance.	• Responses applied force principles to justify why the two-block system decreased in momentum more rapidly due to the increased opposing force from the spring.
• Responses failed to reference the shape of the graph with a connection between the change in momentum and the force exerted on the two-block system.	• Responses analyzed the axes of the graph to equate the change in momentum over the change in time to the force or the slope of the curve.

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?

- 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.
- Work through examples in class that require students to use more than one form of energy as the initial or final when doing conservation of energy questions.
- Emphasize that a justification includes statements and reasonings for why a result occurs. If a graph is being referenced, then quantities from the graph should be included in the response. Simply writing equations and not an explanation as to how the variables change is not sufficient.
- Free-body diagrams can be drawn when developing a justification about forces. Telling students to draw their own free-body diagrams when thinking about forces helps them include the direction in their answer.
- Work through examples using graphs with axes other than position, velocity, and acceleration versus time.
- All graphs do not have linear or horizontal lines to show relationships between variables.
- Functions on graphs can relate variables other than those listed on the AP equation sheet.
- Work through examples in class that require students to discuss all the motions of an object. This should be done for constant and nonconstant acceleration.

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 energy and conservation of linear momentum, impulse, and simple harmonic and oscillations.
- Teachers should direct students to topic questions as well as personal progress check items to monitor progress being made in the mastery of content.
- Teachers can use the question bank to find items that access similar content and skills and create practice assignments for students.

Question 2

Task: Experimental Design
Topic: Resistive Forces Dynamics
Max Score: 15
Mean Score: 10.15

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Derive the differential equation for speed as a function of time for a sphere experiencing a resistive drag force.
- Apply Newton's laws, including identifying and explaining the forces exerted on an object experiencing a drag force with different initial conditions.
- Analyze and interpret sections of a force-time graph.
- Support a claim with evidence from experimental data by recognizing that equilibrium implies that the sum of forces 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.

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 and that a derivation required more than one step.
- Some responses were able to correctly write a differential equation.
- Most responses were able to explain how the initial velocity of the sphere did not affect the forces exerted on the sphere at terminal velocity.
- Most responses were able to draw a best-fit line for the data, although the slope of this line varied significantly.
- Most responses calculated the slope of the line and related it to the given equation using two points on the best-fit line.
- Most responses had difficulty understanding that the prompt which asked the student to describe how the quantities graphed could be used to determine the relationship between the variables meant to explain how the functional dependence between the two variables is represented on a graph.

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 drew a line of best fit that connected only the first and last points on the graph or went through the origin $(0,0)$.	• Responses drew a line of best fit that included approximately the same number of data points above and below the line within a reasonable distance from the actual data points.
• Responses did not include the correct notation for writing a differential equation	• Responses correctly substituted dv/dt for acceleration into a Newton's second law equation.
• Responses did not indicate how to identify the relationship between dependent and independent variables plotted in the graph.	• Responses correctly analyzed the line of best fit to calculate slope and identify trends.

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?

- It seems some students taking AP Physics C are missing the necessary background in Calculus. To address this problem, teachers could review the standard mathematical procedures needed at the beginning of the course and repeat them at the beginning of each unit. Another solution could include collaborating with the Math Department or the AP Calculus teacher to incorporate exercises related to their AP Physics C coursework.
- AP Physics C teachers can go to AP Central under classroom resources and find similar labs, special focus topics focused on data analysis, daily videos, and critical thinking questions.
- AP Physics C teachers could look back at the 2010 prompt question 1 on the AP Physics C: Mechanics exam and try to reproduce the experiment in class using motion sensors and coffee filters (for part (e) different size coffee filters with weight adjustments to keep mass constant). The teacher can also create extensions where the students in groups derive a time-dependent velocity function for the coffee's motion and then compare the function to graphs from the data collected. Once the time-dependent velocity function has been found, the functions for position and acceleration can also be found using calculus. It would be helpful to make groups containing students with different levels of Calculus proficiency to help students with less exposure to higher-level Calculus navigate complicated mathematics.

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 Application
Topic: Torque, Rotational Statics, and Rotational Dynamics
Max Score: 15
Mean Score: 4.16

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.
- Calculate the magnitude of a torque associated with a force acting on a rigid body.
- Calculate unknown forces exerted on an extended rigid body in translational or rotational equilibrium.
- Derive an expression using Newton's second law in rotational form.
- Explain how a quantity changes for different scenarios using physical reasoning.
- Calculate the magnitude and direction of the torque associated with a given force exerted on a rigid body.
- Calculate unknown quantities such as net torque, angular acceleration, or rotational inertia of a rigid body undergoing angular acceleration.

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 the gravitational and tension forces on a rigid body diagram.
- Many responses did not draw the axle force pointing toward the lump of clay; the most common incorrect responses drew an arrow vertically upward.
- Some responses incorrectly included extraneous forces on the diagram. The most common extraneous force included was a normal force at Point A.
- Most responses correctly indicated a balance of two torques.
- Some responses attempted to solve the derivation using the translational form of Newton's second law, which could result in the correct solution but with an incorrect derivation. No credit was awarded for this.
- Some responses incorrectly interpreted the trigonometric functions in the torque relationships for the derivation.
- Most responses related the increasing tension at Point B to increasing the torque.
- Many responses did not state the torque in both situations is the same.
- Some responses incorrectly stated the radius increases when the clay was moved to Point B.
- Most responses calculated the inertia of a nonuniform disk using integration.
- Few responses correctly determined the differential mass in terms of the differential radius.
- Most responses calculated angular acceleration from the torque on the clay and rotational inertia with at least one step to earn a point.
- Some responses used the total rotational inertia of the clay-disk system because the inertia of the disk was calculated in the previous part. This was often used incorrectly to calculate angular acceleration.

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 drew the axle force on the diagram by drawing an upward pointing arrow.	• Responses drew an axle force that points toward Point A and not vertically upward.
• Responses incorrectly derived a force from balancing torques on an object that is not rotating.	• Responses derived an unknown quantity by applying a balance of torques exerted on an object with the correct trigonometric functions.
• Responses did not indicate that torque from the gravitational force is not constant as the angle between the moment arm and the gravitational force changes.	• Responses indicated that the torque increased when the component of the force exerted on the system became more perpendicular to the moment arm.
• Responses incorrectly derived the angular acceleration on the system by applying Newton's second law in rotational form.	• Responses equated the total rotational inertia of the system to the rotational inertia of the disk plus the rotational inertia of the clay.

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 drawing and labeling forces, have students check to make sure what they have drawn accurately matches the scenario. In this case, the total force on the system should be zero, and their force vectors should show this.
- If a scenario looks like rotation is the best approach to interpret the physical situation, make sure to use those concepts in the responses.
- 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.
- Read the question closely to identify if you are supposed to analyze the system or one object.

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.