Chief Reader Report on Student Responses:

2021 AP® Physics 1 Free-Response Questions

• Number of Students Scored	137,229		
• Number of Readers	461 (for all Physics exams)		
• Score Distribution	Exam Score	N	%At
	5	9,498	6.9
	4	22,430	16.3
	3	25,889	18.9
	2	36,255	26.4
	1	43,157	31.4
• Global Mean	2.41		

The following comments on the 2021 free-response questions for AP® Physics 1 were written by the Chief Reader, Shannon Willoughby, Montana State University. They give an overview of each free-response question and of how students performed on the question, including typical student errors. General comments regarding the skills and content that students frequently have the most problems with are included. Some suggestions for improving student preparation in these areas are also provided. Teachers are encouraged to attend a College Board workshop to learn strategies for improving student performance in specific areas.

Question #1 **Task:** Short Answer **Topic:** Energy and Kinematics - projectile motion

Max. Points: 7 **Mean Score:** 1.59

What were the responses to this question expected to demonstrate?

This question was designed to assess the understanding of the following concepts:

Part (a)—Does the response demonstrate an understanding of derivations by demonstrating:

- a conservation of energy-based derivation,
- a kinematics-based derivation, and
- the use of mathematical synthesis to achieve a conclusion?

Part (b)—Does the response demonstrate an understanding of application by demonstrating:

- an understanding of physical relationships expressed mathematically, and
- the application of mathematically expressed changes to the physical problem?

Part (c)—Does the response demonstrate an understanding of analysis by demonstrating:

- the application of graphical analysis, and
- the use of dimensional analysis?

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?

Part (a):

- Derivations appeared to be bi-modal.
- Not all students demonstrated an understanding of the term "derive."

Part (b):

- Not all students were able to correctly analyze an equation when a variable was changed by a factor.
- Imprecise use of vocabulary and vague terms like increase distance instead of horizontal distance.

Part (c):

- Many students didn't demonstrate conceptual understanding in the change in vertical velocity per time of a projectile.
- Many graphed speed instead of vertical velocity.
- Many students did not label the graphs.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• vertical vs horizontal acceleration	• when a_x went to zero instead of g • when a_y went to g and not zero
• ramp time vs flight time	• t =(2√(2gHo) sin θ)/g for flight
• graphing v vs. t vs. h vs t	• graph a line with constant negative (≅9.81) slope
• symmetrical nature of a projectile	• doubling time to max height or in graph and labels were symmetric around the t-axis

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?

- Teach and practice vocabulary like “derive” and “label,” and “briefly.” In the latter case, only the claim and justification need to be addressed.
- Ask students to practice variable manipulation to isolate a specific variable.
- Ask students to identify functional dependence of variable.
- Ask students to apply sketching graphs throughout all units.

Question #2 **Task:** Experimental Design **Topic:** Maximum force

Max. Points: 12 **Mean Score:** 6.64

What were the responses to this question expected to demonstrate?

Responses to this question were expected to demonstrate an understanding of Science Practice 4, Experimental Methods. Students designed an experiment to determine whether the relationship between two variables was more accurately described as linear or quadratic. Students had to realize they would need to perform trials with different values of the independent variable, rod thickness, to determine how thickness affects breaking force. The response also needed to devise practical ways to apply and measure the force necessary to break a rod and be specific about how that force would be applied to the rod using common laboratory equipment. The response needed to include steps to reduce experimental error, such as repeating the same measurement multiple times.

Responses to this question were expected to demonstrate Science Practice 1, Modeling. Students were asked to re-express two opposing narrative models as graphical models. Students were required to sketch a graph of what experimental results would look like if breaking force depended on radius and what the results would look like if breaking force depended on area.

Responses to this question needed to demonstrate well-developed graphing skills, such as making appropriately scaled axes, labeling axes, including units, and sketching an appropriate line of best fit.

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?

In general, the responses showed that students were comfortable designing an experiment to test the relationship between these two variables. The vast majority of responses recognized the need to measure multiple thicknesses and mentioned taking that measurement with an appropriate tool. The vast majority of responses also devised practical ways to measure the force needed to break the rod. A majority of responses included instructions to repeat the measurement with another rod of the same thickness or using terms like repeating with "all, each, or every" rod.

Sketching what a F vs. R graph would look like if student B were correct was a challenge. While most responses included a concave up curve, they did not make the curve specifically quadratic. Many responses did not include clear labels to differentiate the two graphs.

Students did very well creating the graph in part (c); the vast majority of responses earned all three points.

The responses for part (d) were mixed. On the one hand, most responses correctly indicated that student B's model was more closely represented by the graph. However, many responses only justified that selection with a good argument for why student A's model was incorrect rather than an argument in support of student B's model. Many responses pointed out that the graph was curved but did not specifically indicate that the graph showed a quadratic, squared, or parabolic relationship between force and radius and relate that back to area.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Being too general when outlining a lab procedure. An example of this would be "Measure breaking force with a spring scale."	• "Hold one end of the rod and pull the other end with a spring scale until the rod breaks."
• It's unnecessary to include data analysis in an experimental procedure. For example, some responses included a detailed explanation of how to calculate radius from diameter and how to calculate area from radius.	• A good response lists only the necessary measurements for the lab "Measure the radius of all the rods."
• It is unnecessary to discuss gathering materials, organizing a lab station, putting on safety equipment, or cleaning up.	• A good response would not include these steps.
• Repeating a trial and getting results using the same set of independent variables reduces uncertainty, while repeating a similar trial with a different independent variable helps investigate the trend. For example, some responses said, "Repeat with rods of several different radii to reduce uncertainty."	• A good response included deliberately re-taking the measurement of breaking force with a rod of the same thickness.
• Plotting interval data as if it were nominal data on a Cartesian graph is not an appropriate way to scale axes. An example of this would be labeling the major grid lines in the y-axis in part (c) with the force data from the chart [40, 120, 320, 520, 900].	• The major grid marks on a graph should be labeled at equal intervals to create a linearly scaled graph. Responses that labeled the major grid marks at equal intervals from a convenient value just below the minimum data value to the convenient value just above the maximum data value earned this point. Uncluttered responses did not label the minor grid marks.
• Students should become familiar with the difference between the terms equal and proportional.	• "The graph shows that force is proportional to radius squared" would be a good response.

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?

For any question that involves justifying the selection of a particular checkbox, help students avoid accidentally just restating the checkbox. In this question, many responses which indicated model B was better supported by the graph repeated the checkbox as their justification and did not earn the point.

A prompt that uses the word "briefly" is not asking for a long essay.

It's OK if students don't know the name of a piece of lab equipment as long as they sketch a recognizable drawing and identify how the tool is used.

For a lab question, or when designing a lab in class, students should determine the variables that are actually being compared and devise a way to measure those and only those.

Give tests in which students draw and scale a graph by hand. Scaling a graph well is a skill that's learned by practice.

A written description of an experimental setup is often much clearer when accompanied by a picture. For example, in this lab question, a response that said "use the spring scale to measure the force when the rod breaks" would not have earned full credit in part (a). If there were also a picture showing a hand holding the spring scale which was connected to one end of the rod and a hand holding the other end of the rod, the response would earn both the second and third point in part (a).

Practice having students describe graphs in words using specific terms. The graphs students might encounter in AP Physics 1 are outlined on page 352 of the student workbook. Page 353 has ways to help students draw conclusions from lab data. Page 354 helps explain how to justify a response.

During lab time, emphasize why measurements should be repeated and what "reducing uncertainty" means. It's typically not enough to say "repeat several times" without being more specific.

Question #3 **Task:** QQT **Topic:** Momentum
Max. Points: 12 **Mean Score:** 4.30

What were the responses to this question expected to demonstrate?

Responses to this question were expected to demonstrate an understanding of the center of mass of a system of two objects involved in a collision. To successfully complete the problem, students must:

- Predict the velocity of the center of mass of a system.
- Derive an equation for the velocity of the center of mass.
- Graph the speed of two objects involved in a conservation of momentum scenario.
- Determine an expression for final speed when an impulse is applied.
- Apply limiting reasoning and functional dependence to support a claim.

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?

- Students were generally able to determine an expression for the velocity of the disk.
- Students generally did well in graphing speed of the disk.
- Students generally did well deriving an equation for the velocity of the center of mass.
- Students indicated an understanding of conservation of momentum.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Showing the starting point or steps in derivation was lacking. The ability to write an answer in fraction form and apply algebra to arrive at the appropriate expression or equation	• Shows a concrete, fundamental starting point, and applies substitutions and mathematical reasoning to reach the final result. Show substitutions and accurate algebraic steps to arrive at the correct answer.
• Graphing a situation when a net force is acting on the object and then is no longer acting on an object	• A graph that shows the speed of an object when it is accelerating while a net force is acting on it versus the graph for the constant speed for an object which is not accelerating.
• Accurate descriptions of velocities for each stated collision scenario.	• Predicted velocity was provided in terms of v_1 with a clear explanation.

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?

- Review instructional word meanings so that students can differentiate between "determine an expression" and "derive an equation."
- Scaffold student derivations by having them identify fundamental principles, substitute variables and algebraically solve for the variable in question and use clear, individual steps.
- Practice graphing skills all year—specifically for speed and velocity in various situations including units other than Kinematics.
- Provide the opportunity for students to explore each collision type and associated graphs.
- Practice writing mathematical reasoning, limiting reasoning, and functional dependence with and without equations (lab scenarios).

Question #4	**Task:** Paragraph Response	**Topic:** Energy transformation
	Max. Points: 7	**Mean Score:** 2.67

What were the responses to this question expected to demonstrate?

- In terms of physics content, responses were expected to demonstrate an understanding of energy transformations into a variety of forms: gravitational, translational, rotational, and thermal.
- In terms of skills, the question required students to communicate their understanding of energy transformations in graphical and verbal (as opposed to numeric or algebraic) form.

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?

- Content: Responses were generally strong on understanding the basic conversion of gravitational to translational energy. Not as many recognized the difference between rotational and thermal energy, which was the crux of the physical situation posed. Also, a smaller number eschewed an energy approach at all in favor of attempting a dynamics explanation.
- Skills: The majority of graphs drawn earned at least partial credit, either for showing the linear increase in kinetic energy on the incline, or for showing the unchanging kinetic energy on the flat surface. A large number, though, did not communicate the linear nature of the graph either using a straightedge or through a written note to the reader about the intended shape. Most addressed the prompt using physics terminology in logical, connected sentences. Responses that merely restated the prompt repeatedly, or those which attempted to use exclusively mathematical rather than verbal communication, were relatively rare.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• "Because of friction" and "they experience equal friction" are ambiguous statements. "Friction" by itself can mean many different things, not just the thermal energy dissipated by friction.	• "Some of the block's mechanical energy is converted to thermal energy due to the friction on the ramp."
• Gravitational potential energy can be converted to forms other than translational kinetic. The most common incomplete response was "the objects have the same translational kinetic energy at the bottom because they have the same potential energy at the top." • Even though the kinetic energy formula is quadratic with speed, that doesn't mean that a graph of kinetic energy vs. <u>distance</u> must be quadratic.	• "The objects start with the same gravitational energy. They convert equal amounts of energy to work done by friction for the block, and rotational kinetic energy for the cylinder." • A linear graph of kinetic energy vs. distance – in this case, gravitational energy decreases linearly with distance, so to conserve mechanical energy, total kinetic energy must increase linearly with distance.

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 verbal responses. Students whose problem-solving practice has been predominantly numerical or algebraic are at a disadvantage on the AP Physics 1 exam, especially on the paragraph response prompt. They need practice writing sentences, even short sentences; and they need authentic feedback on those sentences such that they understand when their use of physics terminology is correct and clearly communicative of their understanding.

Question #5 **Task:** Short Answer **Topic:** Rotational Kinematics, Torque, and Angular Acceleration

Max. Points: 7 **Mean Score:** 3.09

What were the responses to this question expected to demonstrate?

Understandings—Responses were expected to:

- demonstrate an understanding of torque, specifically the net torque exerted on a system, and the effect of force and radius on torque. A mathematical representation was required in addition to a conceptual explanation.
- explain why a change in velocity occurred by using an analysis of the torques exerted on the system.
- express the motion of the pulley both in written and graphical form.

Skills—Responses were expected to:

- demonstrate an ability to create a mathematical representation of the net torque on the system.
- construct explanations and make claims about the motion of the pulley based on the concept of torque.
- make connections between the concepts involved with rotational kinematics and those involved with torque.
- create a graphical representation for the angular velocity with respect to time.

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?

- Content:
    - Most responses demonstrated the basic understanding that torque is related to both force and distance from the axis by making some attempt to relate force and radius to torque in part (a)(ii). However, many responses failed to correctly express the force due to gravity and simply used the mass of the block rather than the product of the mass and the acceleration due to gravity. A number of responses included "sinθ" in the final answer, which may hint at a lack of knowledge of which angle θ represents in the torque equation. The addition of part (a)(ii) required students to understand this relationship on a conceptual rather than a purely mathematical level. Many incorrect responses cited only the increased radius of the pulley from which object 1 was hanging and neglected to address the larger mass of object 2. Some responses attempted to answer the question using an analysis of the forces exerted on object 1 rather than the net torque on the system.
    - For part (b), asking the students to explain their reasoning (rather than how or why) allowed for a wide range of approaches. Many students referenced the fact that the pulley would slow down when the string was cut, while others focused on the net torque before and after the cut and how that affected the angular acceleration and, in turn, the direction of the angular velocity. Still others used the idea of inertia to describe how the pulley would continue to rotate counterclockwise for some time even though the acceleration would immediately switch to clockwise.
    - The majority of the graphs received at least partial credit, but one common error was showing a discontinuity at t_c and incorrectly starting the second part of the graph at a velocity of zero. Another common error was drawing the slope curved rather than straight.

- Skills:
    - Many correct expressions for the net torque showed no steps to the process. Many responses did not give the answer in terms of the given variables and fundamental constants, dropping the subscripts on m_0 and r_0 and leaving "sinθ" in the final answer. Some responses showed no attempt, or a completely incorrect attempt in part (a)(i) but went on to answer part (a)(ii) perfectly, sometimes even giving correct expressions for the torques within the explanation, showing a lack of skill in deriving a mathematical expression even while understanding the situation conceptually. In part (a)(ii) most responses gave a reasonable attempt at an explanation (whether or not it was correct). Only a very small number of responses showed math with no attempt at an explanation using words.
    - Part (b) required making connections between the torques exerted on the system and the resulting kinematic quantities associated with the system's motion, as well as making predictions about the directions of those quantities. Most responses demonstrated an ability to connect torque to the direction of angular acceleration but often did not correctly relate that to the angular velocity. Responses often indicated a misunderstanding of the question and incorrectly compared the angular velocity and acceleration *before* the string was cut to their corresponding directions *after* the cut.
    - A fair number of the graphs drawn for part (c) were clear and precise, but still many were ambiguous, having not been drawn with a straightedge or clearly labeled to indicate the intended shape. Further, some responses showed a change in the slope of the graph slightly before or after t_c and were unclear whether this was due to careless drawing or a true lack of understanding of the physics.

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 force due to gravity is equal to the mass rather than the product of mass and acceleration due to gravity. Often "g" was completely absent from the derivations for part (a)(i). • The net torque is equal to the sum of the magnitudes of the two torques, neglecting their directions.	• $\tau_{net} = \tau_1 - \tau_2$ • $\tau_{net} = (m_0 g)(2r_0) - (1.5m_0 g)(r_0)$ • $\tau_{net} = 0.5m_0 g r_0$
• The less massive object accelerated down due solely to the larger radius of its pulley (with no regard to the mass of the other object).	• "The torque exerted by object 1 is larger than that exerted object 2 because the product of its mass and radius is larger than the product of mass and radius for object 2."
• The direction of angular velocity switched from counterclockwise to clockwise immediately after the string was cut. This misconception was expressed both in the written explanation for part (b) and in the graph, by showing a discontinuity at t_c.	• "Prior to t_c the pulley was moving in the counterclockwise direction. When the string was cut, the net torque and therefore also the angular acceleration switched to the clockwise direction. However, due to the system's inertia, the angular velocity would require some time

	to slow down and stop before changing directions.”
• The graph of the angular velocity vs. time is horizontal before t_c. • The graph of angular velocity vs. time is nonlinear either before or after t_c or both. • The change in direction of acceleration happens gradually or continues in its original direction for some time after t_c as shown by a curve rather than a sharp point.	• An example of a correct graph is shown in the rubric.

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 should be taught to use a straightedge for graphs that they intend to be linear or, if unavailable, to label the line as straight to avoid ambiguity.
- “Derive” (as well as other task verbs) have specific meanings defined in the course and exam description.
- Students should be aware of these definitions and have opportunities to practice using them:
  - Provide students with the list of task verbs from the *AP Physics 1: Algebra-Based Course and Exam Description* at the beginning of the year.
  - Refer to it throughout the year to have students practice these tasks.
- The effect of the *product of* force and radius on torque should be emphasized over simply radius.
  - Provide “ranking tasks” that ask students to compare and rank various scenarios that are identical except for the force and radius values. This enables students to practice using the torque equation and clearly see the effect of force and radius on various situations in an efficient way.
- Students could use more practice with graphing angular kinematic quantities, focusing on the relationships between angular displacement, velocity, and acceleration with respect to time, and with what happens when acceleration changes.
  - Provide students with a side-by-side comparison of the linear kinematics graphs with their angular counterparts to illustrate the similarities. Because linear kinematics is often the first unit taught and rotational motion is often the last, this also provides a nice review of the former.
  - Task students with sketching graphs of these quantities in numerous scenarios.