Chief Reader Report on Student Responses:

2019 AP® Physics C Mechanics Free-Response Questions

Set 2

• Number of Students Scored	57,131		
• Number of Readers	377 (for all Physics exams)		
• Score Distribution	Exam Score	N	%At
	5	21,517	37.7
	4	15,268	26.7
	3	9,924	17.4
	2	5,710	10.0
	1	4,712	8.2
• Global Mean	3.76		

The following comments on the 2019 free-response questions for AP® Physics C Mechanics 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:** Newton's second law **Topic:** Modified Atwood machine

Max. Points: 15 **Mean Score:** 7.58

What were the responses to this question expected to demonstrate?

The responses to this question were expected to demonstrate the following:

- Problem-solving strategies that would allow students to break down a complex problem into manageable pieces
- An understanding of Newton's laws and an ability to apply Newton's second law to form one or more algebraic expressions
- Apply Newton's third law to couple these algebraic expressions and simplify them
- Apply algebra and trigonometry to arrive at the correct answer

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

- The students generally demonstrated the ability to apply problem solving strategies and arrive at equations based on Newton's Second Law.
- Most students could arrive at expressions relating net force to mass times acceleration, or set force equal to zero when in equilibrium, which included the right set of terms but there were often mistakes in those terms.
- The students could often take coupled expressions and simplify them to a single expression. It was very common for the student's final answer to have a sine/cosine error or a sign error in one or more term.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Incorrect application of trigonometry.	• Including the cosine with the friction term and sine with the x component of weight.
• Not having the direction of friction along T_2.	• Results in an incorrect sign of the friction term.
• Not including initial statement of Newton's second law.	• Results in missing some forces in the problem.
• Normal force being upward.	• The normal force is always perpendicular to the surface.
• There is still tension in the cable between the blocks when the string between block m and the sphere breaks and the objects are allowed to slide down the incline.	• Although the magnitude of friction is different on each block, they undergo the same acceleration as they slide down the incline, and thus T_1 becomes zero.

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?

- In many courses, friction and inclined planes are taught in separate units and rarely discussed in situations like the experiment in this question. If time allows, after Newton's Laws, Dynamics, and Friction are covered, it is recommended that problems involving all three topics are discussed in detail, so that students can understand the overarching principle and how they are connected and not isolated physical phenomenon.

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

- AP Physics C teachers can find useful resources on the course audit webpage and the AP Central home page for AP Physics C. In addition, topic questions that are tied to specific learning objectives and science practices can be found on the new AP Classroom.
- The new AP Physics 1 Student Workbook contains many helpful scenarios, which address topics and skills also covered in AP Physics C. These scenarios can be modified or scaffolded as needed for Physics C students.
- The AP Physics Online Teacher Community is active, and there are many discussions concerning teaching tips, techniques, and activities that AP Physics teachers have found helpful. It is easy to sign up, and you can search topics of discussions from all previous years.
- New teachers (and career changers) might want to consider signing up for an AP Summer Institute (APSI). An APSI is a great way to get in-depth teaching knowledge on the AP Physics curriculum and exam, as well as network with colleagues from around the country.

Question #2 **Task:** Graphing **Topic:** Kinematics
Max. Points: 15 **Mean Score:** 8.13

What were the responses to this question expected to demonstrate?

The responses to this question were expected to demonstrate the following:

- How to perform velocity and position calculations for both constant and nonconstant acceleration:
  - Working with an object that is undergoing nonconstant accelerating motion requires primarily the understanding that the kinematics formulas are no longer applicable.
  - Calculus is necessary to obtain the necessary results.
- How to graph velocity of an object over time throughout the situation given in the problem. This initially involves a nonlinear motion where the speed of the rocket is increasing but at a slower rate, followed by free-fall motion where the rocket continues to move upward for a short period of time until the speed of the object reaches zero (and thus maximum height) and comes back down with the same acceleration.
- Students were also required to demonstrate the fundamental understanding that while the engine is being fired, the energy of the rocket itself is not conserved. In fact, it is gaining energy due to the work done by the engine on the rocket. However, once the fuel is exhausted the Law of Conservation of Energy applies.

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?

- Student responses showed that students are generally able to recognize when they need to use calculus to find velocity and position rather than kinematics equations with constant acceleration.
- Many student responses showed inadequate calculus skills, including incorrect integration and omission of either limits of integration or a constant of integration.
- Relatively few students were able to correctly graph the transition from velocity while the rocket engine was firing to velocity under free-fall conditions. In fact, many assumed that acceleration would be zero at max height and used the acceleration expression given in the problem to find the time the rocket reached the top by equating it to zero.
- Students generally used conservation of energy correctly.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• In (d) many students thought that the max height occurs when the engine shuts off, even though the rocket has a nonzero upward velocity at that moment.	• The rocket rises an additional amount as gravity slows it down to a halt, and the max height is the sum of height at the moment the engine shuts off plus the additional height during free fall.
• Acceleration = 0 at the top.	• Acceleration of the rocket after engine shuts off is a constant – g, or – 9.8 m/s^2, including at the top of the motion. At that point, only velocity is equal to zero.
• Kinematics equations such as $v_f = v_o + at$ and $v_f^2 = v_0^2 + 2ad$ can always be used once an acceleration is known or given.	• Calculus (i.e., integration and derivation) is correctly applied to sections of the problem dealing with a nonconstant acceleration while the engine is firing.

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?

- Misconceptions such as the ones mentioned above are very hard to overcome. Even after many lessons and repeatedly mentioning them during class most students will continue to make such mistakes. The most practical method to correct them is allowing students to experience them first hand and discover their own misconceptions instead of lecturing them about it. A lab or a project is an ideal situation for this.
- As for the calculus part, it is imperative that in an AP Physics C course, students have a strong background in calculus. And that usually means complementing what they learn in their math class or AP Calculus class with more exercises that involve applications of calculus concepts. Working closely with the math department or faculty is high recommended.

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

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Question #3 **Task:** Loop de-loop **Topic:** Conservation of energy
Max. Points: 15 **Mean Score:** 5.18

What were the responses to this question expected to demonstrate?

The responses to this question were expected to demonstrate the following:

- Recognizing the forces in a system contributing to the centripetal force in a system with a vertical loop where the gravitational force needed to be considered properly
- Relating rotational velocity to linear velocity and the dependence on the radius of the circular motion involved in spinning about a central axis
- Applying conservation of mechanical energy in a complex system with translational and rotational kinetic energy and with both initial and final gravitational potential energy
- Reading a data table and interpreting a graphical representation of that data, as well as constructing a graph and plotting given data in a meaningful way
- Being able to use this graph to deduce other related parameters of the system that were not directly measured

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?

- Student responses often neglected to address the centripetal force content and the skill of recognizing the contributing forces.
    - A majority of students often answered part (b) as part (a) with a haphazard mix of related equations appearing in spaces allocated for (a) or (b) answers while ignoring or failing to explicitly answer part (a) in the process.
- Student responses fairly often addressed the content of circular motion regarding rotation around a central axis and the skill of relating rotational to linear velocity.
- Student responses often addressed conservation of energy in some way, though often this was not shown explicitly. The student skills in applying this principal were addressed well by examining how many energy terms students considered.
- Student responses generally did address graphical representation in constructing and interpreting a graph. Many students were able to construct the graph from the data provided and draw a linear best fit line.
- A large fraction of students demonstrated their lack of understanding in constructing a graph through lack of structure in systematically laying out the structural elements in scaling, origin, and labeling—including units. Many students did not create a best fit of their data with a straightedge and subsequently had a harder time interpreting their own graph.
- Student responses often neglected to address the centripetal force aspects of the circular motion around the loop.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
Part (a) • Not following directions, jumping directly to answer, writing only the result • Not distinguishing among specific variables used in this problem, little “r” vs. big “R” • Writing a lot of other stuff in the answer space for this part that may or may not be useful • Leaving the v^2 result as is without simplifying to say what v equals by itself	• Start with a general equation since asked to “Derive,” then insert specifics relative to this question to arrive at final answer: v = sqrt(gR). • Use “R” in the final answer, since that is the relevant radius. • Contain only stuff related to this part in this part's answer space with no extraneous information • Present the final answer directly as “v = sqrt(gR)”
Part (b) • Writing the answer to this part in space allocated for the previous part without noting that in any way • Write a bunch of equations relating to various pieces involved in the solution without making it clear how the pieces fit together • K=U • mgh = 1/2 mv^2 • mgh = 1/2 Iw^2 • mgh = 1/2 mv^2 + 1/2 Iw^2 • Moment of Inertia “I” is left in final answer • Substitue vr for omega • Previously found information in earlier part is not used, leaving a variable "v" as part of the final result	• Write only relevant information to this part in this part's answer space • Start with a clear statement saying what they're doing, either "conserve energy" in words or in equation form, indicating that total starting energy equals total energy at the ending point. • Delta K + Delta U = 0 • mgh = 1/2 mv^2 + 1/2 Iw^2 + mg2R • mgh = 1/2 mv^2 + 1/2 Iw^2 + mg2R • mgh = 1/2 mv^2 + 1/2 Iw^2 + mg2R • Moment of inertia “I” is replaced with bmr^2 • Substitute v/r for omega to simplify • Result from (a) that v = sqrt(gR) is substituted for v everywhere to simply result in terms of known parameters and constants

Part (c) • Neglecting units of axes • Axis values start at zero • Data in data table assumed in monotonically increasing order • Plots only some of the points clearly, either omitting points that end up on grid line intersections or making them so faint that they are not visible to the naked eye • The precise location of some data points is random • Line drawn by unsteady freehand: curves and wiggles • Line drawn includes multiple lines, back and forth scribbles • Line drawn systematically on one side or the other of data points • Line must start at origin of graph	• Specify the units corresponding to numbers along each axis • Start axis values at a reasonable number that allows data to be spread across at least half of the plot in each direction • Realize that data in table associates numbers along any given row and that each of these numbers doesn't have to necessarily follow in order according to numbers in previous or following rows • All data points plotted with a clear, dark dot for each • The location of each data point is consistent with the chosen grid scale • Line is drawn with a straightedge • A single line is drawn amidst the data points • Line drawn is a "best fit" by eye splitting differences so not all points are on one side •
Part (d) • Graph information is not used when given the opportunity. • If graph information is used, how it is used is not noted • Final answer not highlighted among other numbers present. • Numbers used along the way are not necessarily in a logical order. • Answer appears magically.	• Use information from the graph (slope, intercept, or equation of line). • Work used to determine any key parameters is shown, either mathematically or by notations made on the graph, such as the slope or intercept deduced from the fit line. • Final answer is highlighted by drawing a circle or box around it. • Final answer is the last after a progression of numbers calculated in a logical order along the way. • State the reasoning for a particular answer, either in words and/or with numbers and mathematical operations

	that lead to that answer, b = 0.8 using equation of line h = 0.2 b + 1.0.
Part (e) • Numbers and mathematical operations are shown without any context of what they or their result represents. • Previously found information in earlier part is not used. • Final answer contains one or more variables as part of the final result.	• The equation into which numbers are substituted into is written first, then the numbers are shown along with the final answer result. • Equation found in part (b) is used to solve for radius R using a value of (h, b) from either the data table, equation of line, or above information. • Final answer is stated with numerical value for R = 0.4.
Part (f) • Answer is checked with no justification.	• Justification for checked answer relates specifically to question and explains logic involved, such as: center-of-mass of object at starting point is higher than the contact point P, the final height of center-of-mass at point A is lower by “r,” and/or the radius of the centripetal circle at point A is smaller by “r,” which all enable a lower starting height since less initial gravitational potential energy is required.

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?

Your response should:

- Have students draw a free-body diagram as appropriate to begin tackling a problem. This is especially important in equilibrium situations where students need to set up an equality, $F_g=F_c$ for example. Then have students write the equality with the forces—not the formula terms. I find that this helps them lock onto the physics before they begin doing algebra.
- Students are so accustomed to dropping a ball to the ground in which conservation of energy ends up as mgh = 1/2 mv^2 that they use that in all cases, forgetting about rotational kinetic energy and also forgetting that if the final height isn't zero that it also has a final potential energy term g2R in the final total energy sum. Emphasize always that it's the total energy that is conserved at all points, everywhere along the path of an object at any time, not simply at the top and bottom of the motion. Only sometimes are various pieces equal to zero, most of the time all pieces are present and nonzero.
- It is important to realize if/when Logger Pro or any other software is auto scaling, that students can do this themselves when they plot, and that the y-intercept of a line does not have to be zero, especially when the data points do not represent (0, 0) well. The min and max range of the axes should make sense for that data. It's nice to know how far away the zeroes are, but they are not always desired on the plot itself.
- Have students call out the topic title in their work on a problem. For example, simply writing "Conservation of Energy," even as "COE" sets students up for success and solidifies for the grader what (key) concept the student is trying to convey. After conveying the key concept, then (on the next line) write out the variable names—U, K, W, etc. Finally, begin inserting formula variables and not before. This often makes a two to three point difference on student question scores on a 12- or 15-point question.
- When drawing a line of "best fit," expect students to always use a straightedge. This is an easy point to earn and just as easily lost. When a question asks a student to "use the line," ideally they should determine the equation of that line by finding the slope and intercept, or at least when answering that question be sure to indicate by arrows on the graph the spot where they did the interpolation by eye for that particular (x, y) point of interest.
- Any justification is better than a blank justification and should at least reference a specific physical quantity that changes as a result conceptually if they are unable to detail exactly how (given limited space and time available on the exam). Tell students to go back and look at the related equation and see if they can tell what would happen if one of the parameters was increased or decreased; would that make the result larger or smaller? Sometimes it's easier to see in the math than to fully grasp the concept. Sketching the picture helps, as does making the parameter more extreme. For example, by sketching a large-sized object at the starting point P or the top of the loop point A, a student may notice the center-of-mass being much higher or lower, respectively, which should lead them to the right conclusion, which they may not have realized from only the little picture of the ball provided on the exam.

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