Chief Reader Report on Student Responses:

2018 AP® Physics C: Mechanics Free-Response Questions

• Number of Students Scored	57,399		
• Number of Readers	380 (for all Physics exams)		
• Score Distribution	Exam Score	N	%At
	5	17,335	30.2
	4	15,662	27.3
	3	11,331	19.7
	2	7,307	12.7
	1	5,764	10.0
• Global Mean	3.55		

The following comments on the 2018 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: Data analysis** **Topic: Free fall and Newton's law**
Max. Points: 15 **Mean Score:** 9.41

What were the responses to this question expected to demonstrate?

- A basic understanding of kinematics and students' ability to linearize experimental data using kinematic relationships.
- Graphing skills and students' ability to analyze both graphed and modeled data.

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

Student responses mostly addressed the course content in this question. In general, most students wrote only partial statements or mathematical expressions instead of complete responses. The same thing can be said for the following skills: setting up graphs, graphing data, completing a best fit straight line, calculating slope, and taking derivatives.

It was clear from the responses that many students are not well trained in the art of manual graphing. Often students chose incorrect or awkwardly/unnaturally spaced scales that made accurate plotting of points difficult. Students also had difficulty in their justification of part (a) where they would often simply restate the check-box choice in words. Justifications are not evaluated on length, but on the students' reasoning and ability to connect concepts to the given situation. Responses were often factual but incomplete.

Students also commonly did not recognize that specific steps must be shown in a derivation. For instance, students should specifically show that velocity is the time derivative of the position function.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
Simple rephrasing of the statement in the question indicating that the extended time resulted in a decrease in the calculated value for 'g', quoted from the problem statement. Use of h/t (given) to calculate the average velocity (speed) but used as a final velocity in setting up graph	A longer measured time over the same distance (h) results in a lower calculated change in velocity producing a smaller calculated 'g'.
Not correctly labling axis with variable and units. Failure to use a straight edge to create a best fit "strait line". Failure to visually best fit data. Many responses showed a line connecting only the first and last points in graph. Forcing of best fit line through zero, even when data suggested otherwise.	Use of a straight edge Best fit that shows about the same number of data points above and below. Best fit shows adjacent points split by best fit straight line.

Slope calculation using data (points) not on the best fit line. Slope calculation presuming zero for one point on best fit line, even when data suggested otherwise. Failure to "derive"; the standard for this is higher and requires students to show that they are taking a time derivative. Failure to carefully read the question and recognize that the coeficients called out are required in order to calculate the final velocity.	Circled use of points on best fit line not part of data set used to calculate slope. Complete use of two data points used (shown) demonstrating rise/run. $dy/dt = v = 2At+B$
Graphing skills can be improved. Teach students how to make a graph.	Create logical scales based on 5-tick grids.
Students fail to recognize that there is a difference between an instantaneous velocity and an average velocity. Students should provide proper units on a graph. Students should draw a best fit line as opposed to forcing the line through the origin or a first point to last point connection. Suggest that students always use a straight edge when drawing lines of best fit. Solid lines, not sketches, work for best fit lines. Students should properly linearize an equation and then graph it. Responses should use the slope to find a physical constant. Students should learn to properly calculate a slope and show their slope calculations using all four coordinate points. Some students don't use points ON the best fit line to calculate a slope. Students should recognize what it is to DERIVE an equation. Some students didn't set up a proper percentage error calculation.	

Students shouldn't indicate physical quantities when asking for quantities to plot in linearization. Justifications should be brief and to the point. Quantitative reasoning is preferred over descriptive reasoning.	

Based on your experience at the AP® Reading with student responses, what advice would you offer to teachers to help them improve the student performance on the exam?

Teachers should have students regularly graph data and practice best fitting it by hand, especially data that does not fit through zero.

- Students should set up graphs structurally: scale, labels, units, and title. Teachers can have students do this as part of their homework problems in relaying proportional relationships.

- Require students to use a straight edge/ruler when best fitting linear data.

- Teachers should require students to calculate slope using non-zero points on best fit line but not part of data set.

- Review with students the different level of expectations for "Calculate," "Determine," and "Derive."

    - **Calculate -** a student is expected to show work leading to a final answer, which may be algebraic but more often is numerical.

    - **Determine-** indicate that work need not necessarily be explicitly shown to obtain full credit. Showing work leading to answers is a good idea, as it may earn a student partial credit in the case of an incorrect answer, but this step may be skipped by the confident or harried student.

    - **Derive-** This is more specific and indicates that the students need to begin their solutions with one or more fundamental equations, such as those given on the AP Physics C Exam equation sheet. The final answer, usually algebraic, is then obtained through the appropriate use of mathematics.

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

- Teachers can find useful resources on the Course Audit webpage and AP Central Home Page for AP Physics. Mechanics and Energy Module, the AP 1 and AP 2 lab manual may provide practical application of these concepts and the reference guide for students, Quantitative Skills in the AP Sciences.

- The AP Physics Online Teacher Community is active and there are many discussions concerning teaching tips, techniques, and activities that many 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 APSI. An APSI is a great way to get in-depth teaching knowledge on the AP Physics curriculum and exam and is also a great way to network with colleagues from around the country.

- **Quick Calculus: A Self-Teaching Guide, 2nd Edition;** Daniel Kleppner, Norman Ramsey

Question #2	Task: Calculate using graph and calculus	Topic: Elastic collisions
	Max. Points: 15	**Mean Score:** 6.83

What were the responses to this question expected to demonstrate?

- An understanding of elastic collisions, impulse-momentum, and elastic potential energy.
- The ability to apply integral calculus to solve for impulse applied to an object.
- Overall, the knowledge of how to determine if a collision is elastic or not. In order to properly do this, students needed to understand the relationship between impulse, force, and the change in momentum.
- The ability to integrate the function and use that result to determine the velocities of each cart after the collision occurred. In addition, once students determine the velocities, they were asked to demonstrate, through the conservation of energy, that the collision is elastic.
- Finally, students were asked to find the maximum energy stored in the spring during the collision.
    - A comprehension of conservation of momentum and the conservation of energy.
    - Graphical analysis skills.

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

- Most students correctly set-up the integral of the given force function, with correct limits, in order to calculate the impulse given to cart 1.

- Students who attempted to solve part (d)(ii) through the use of Hooke's Law were successful in determining the value of the maximum spring force, calculating the maximum compression, and solving for the maximum elastic potential energy.

- Most students realized that they needed to integrate the function with respect to time to get the impulse. Considering that collisions and conservation of momentum are fundamental concepts that every AP Physics course should cover in depth, the question was appropriate to the level that the students should be able to handle.

- The responses seemed to indicate that most students were able to properly find the impulse and relate it back to the speeds, but the most common errors showed that while students understood which equation to use, many students determined the speed for the wrong cart. Another indication that students were just throwing equations at the problem was the rare, but not uncommon, use of the relative velocities equation used to find the coefficient of restitution. Many students had memorized this equation and were using it for parts (b) and (c) when, in fact, using that equation in these parts made the assumption that the collision was elastic ($e = 1$) before they were asked to prove that. Responses to part (d) also indicate that many students were throwing equations at the problem instead of thinking through the question and their response.

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

- Students should have been drawing diagrams and labeling vectors and carts, along with providing numerical solutions, to more thoroughly demonstrate their understanding of the concepts being tested.

- There seemed to be a misunderstanding of the basic concepts of conservation of energy and impulse. Students didn't seem to understand how to properly apply conservation of energy principles and use those principles to solve for the unknown. Students were not always consistent with using the impulse to solve for a cart's velocity since the impulse on one cart would be the negative impulse delivered to the second cart.

- Few students were determining, labeling, or otherwise indicating a coordinate system with which to make reference to + or – velocities. The questions asked for speed, but this may have caused students to ignore the +/- references altogether while focusing on a number from the equation rather than what that number meant.

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
Some students didn't correctly indicate the integral of the F(t) with respect to dt; students either indicated with respect to dx or did not indicate with respect to which variable they were integrating.	$\int F\,dt = \int_0^{0.16} 3200t^2 - 500t\,dt$
Incorrect limits selected – 0 to 0.18 seconds.	Correct limits were 0 to 0.16 seconds.
Students did not properly show all mathematical work when prompted to "calculate."	Students must start with a known physics formula and show step by step, including numeric substitutions, how a final answer is achieved.
Responses failedto relate the integral of the force funtion to impulse=change in momentum to solve for the final velocity of cart 1.	
Some responses did not indicate impulse=mass of cart 1 times the change in velocity of cart 1.	
Some students used special case of elastic, head-on collision "formulas," without showing derivations of these "formulas."	
Some responses mistakenly defined an elastic collision as objects "don't stick together"	
When attempting to answer part (d)(ii) using conservation of energy, responses did not include the final kinetic energy of the system.	
Responses did notuse correct units for impulse.	

Based on your experience at the AP® Reading with student responses, what advice would you offer to teachers to help them improve the student performance on the exam?

- Use or develop a consistent coordinate system, draw diagrams, clearly label the diagrams so that students have a full picture of what is going on. Without the defined +/- coordinate system, students can confuse the objects and what those objects are doing.
- Define the system being worked and what, if anything, is external or internal to that system. This will help students better understand the concepts of conservation of energy and momentum.
- Show students how to develop a solid problem solving method, with strategies designed to help them piece together clues given in the problem so that they better understand what physics principle they need to use. Focus on applying the concepts and showing students how the math and equations better relate to those concepts.

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

- Teachers can find useful resources in the Course Audit webpage and AP Central Home Page for AP Physics. The AP 1 and AP 2 lab manual may provide practical application of these concepts and the reference guide for students, Quantitative Skills in the AP Sciences

- The AP Physics Online Teacher Community is active and there are many discussions concerning teaching tips, techniques, and activities that many AP Physics teachers have found helpful. It is easy to sign up and you can search topics of discussions from all previous years.

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Question #3

Task: Calculate

Topic: Rotational kinematics and dynamics

Max. Points: 15

Mean Score: 4.43

What were the responses to this question expected to demonstrate?

- The ability to determine the moment of inertia of an object with varying mass density.
- An understanding of how to use the principle of superposition and the rotational inertia of basic objects to determine the total rotational inertia for complicated objects.
- The ability to determine the forces that are acting on the object as it rolls without slipping.
- An understanding of the conservation of energy as the hoop moves.

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

- Student responses could have more thoroughly addressed the course content related to this question. This problem required an understanding of how to calculate the moment of inertia, how torque and angular velocity are related, and rotational dynamics.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
Students often confused variable and constants (L = r or x). Many students did not recognize non-linearity of λ when relating dm to dr. For example $dm=(2M/L^2)dx$ when it should be $dm=(2M/L^2)x\ dx$. Many students integrated the given non-uniform linear mass density function $\lambda=2M/L^2\ x$ (and determined the rod has mass M), rather than starting with I=<integral of> r^2 *dm*.	Ability to integrate a non-uniform linear mass density to obtain moment of inertia. This question definitely separated the students that could integrate properly and those that could not.
Many students attempt to use the parallel axis theorem. Students forget to add **3** rods or used an incorrect rod formula (1/3 ML^2 or 1/12 ML^2 when it should be 1/2ML^2). Many students did not provide derivation and simply give final answers with no supporting work.	Ability to sum multiple moments of inertia. Since the algebra was very easy, many students who knew their physics simply gave a correct answer and lost points.

• Many students used an equation for linear dynamics, $F=ma$ or $F\Delta t = m\Delta v$, when they should use angular, $\tau=I\alpha$ or $\tau\Delta t=I\Delta\omega$. Many students did not start with fundamental law/theorem or equation from the equation sheet. Many students equated torque and force. Many students did not express their answers in the terms given.	Ability to derive an equation that combines kinematics with torque to obtain a final angular velocity.
Incorrect point of exertion: The most common error was stating the normal force is applied at the center of the system. Another common error was indicating the weight force is applied at the contact point between the hoop and ramp. Extra forces like F_C, F_A: These forces were usually justified as the force required for the system to continue to roll up the ramp. Many students incorrectly stated that friction was down the incline when it should be up the incline. Student responses incorrectly labeled "friction" as "kinetic friction." Some students answered that the normal force must be vertical to balance the force weight.	Ability to draw and label forces acting on a wheel rolling up an incline without slipping.
Many students offered vague or incomplete justifications for direction of friction; e.g. "friction opposes motion" when they should have said "friction opposes the direction of rotation." Many students equated gravity and normal force. Many student responses indicated that there is relative motion between the hoop and the ramp at the contact point between the two.	Ability to justify the direction of the forces. Students earned partial credit for incomplete or partially incorrect force diagrams.

Many students did not express their answers in terms given. Many students did not include KE_T in initial energy. Many responses did not replace r with L when subtituting $v=\omega r$. Some responses incorrectly stated $v=\omega/r$. Many students did not replace M with 4M in both the final solution. Other students replaced M with 4M in either the linear kinetic energy or the gravitational potential energy, but not in both.	Ability to derive an equation from the conservation of energy for a wheel rolling without slipping up an incline.

Based on your experience at the AP® Reading with student responses, what advice would you offer to teachers to help them improve the student performance on the exam?

- Ensure students know how to determine the rotational inertia of complicated objects by summing up the rotation inertia of their parts.
- Make sure students understand when to use just rotational kinetic energy, only linear kinetic energy, and when to use both.
- Spend time on free-body diagrams for rotational motion so students understand the importance of the point of exertion of the forces. Also spend time on the direction of friction for different rolling objects.

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

- Teachers can find useful resources in the Course Audit webpage and AP Central Home Page for AP Physics. The AP 1 and AP 2 lab manual may provide practical application of these concepts and the reference guide for students, Quantitative Skills in the AP Sciences.

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