Chief Reader Report on Student Responses:

2019 AP® Physics 1 Free-Response Questions

- Number of Students Scored: 161,071
- Number of Readers: 377 (for all Physics exams)
- Score Distribution

Exam Score	N	%At
5	10,750	6.7
4	29,358	18.2
3	33,063	20.5
2	46,160	28.7
1	41,740	25.9

- Global Mean: 2.51

The following comments on the 2019 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:** Other, graphing **Topic:** Kinematics

Max. Points: 7 **Mean Score:** 3.49

What were the responses to this question expected to demonstrate?

In this question, students must demonstrate an understanding of the center of mass of a two-object system and the rotational motion of sliding or rolling objects. To successfully complete the problem, students must:

- Indicate that the velocity of an object on a horizontal surface with negligible friction remains constant.
- Show that the center of mass velocity remains unchanged in a collision.
- Recognize that a constant force leads to a linear change in velocity with time, as occurs both while the sphere is pushed by the plunger and while it slides across a frictional surface.
- Demonstrate skills presenting data in a graph.
- Reason that a net torque leads to a change in angular momentum. Specifically, a tangential force at the surface, such as friction, produces a torque that leads to an increase in angular momentum in this problem, while a force directed towards the center of the sphere, such as the force imposed by the plunger, gravity, or the normal force, does not produce a torque.

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 generally did well in graphing the center of mass speed, often recognizing the initial linear increase in speed, the constant speed in the absence of friction, and the linear decrease in speed in the presence of friction, as well as drawing a single, qualitatively accurate graph from t_A to t_F. They frequently incorrectly included an abrupt decrease in velocity at t_E.

- Students often recognized segment C to D as a region leading to a change in angular momentum and that angular momentum is associated with whether the sphere is rolling or not. However, students often did not demonstrate understanding that friction causes a torque which leads to a change in angular momentum.

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

- It was common for students to include an abrupt decrease in velocity at t_E on the graph, perhaps considering only the motion of block 1 and not recognizing that the center of mass velocity remains constant when embedded in this multi-step analysis.

- In part (b) students often did not clearly indicate that friction leads to a torque which produces a change in angular momentum. While most students correctly checked "C to D" in their responses, students often attempted to answer the question using only linear quantities, incorrectly stating that friction reduced the speed of the object and therefore decreased angular momentum.

- Less commonly, students incorrectly indicated that the sphere stopped rolling and the angular momentum was zero when a torque is no longer present, such as on the frictionless surface D to E at the end of the track, or that the plunger force from A to B did produce a change in angular momentum.

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• The center of mass speed drops abruptly in a collision.	• A horizontal line indicates that the speed of the center of mass is constant during a collision.
• An object rolls if there is friction and does not roll if there is no friction.	• Friction can lead to a torque on a sliding object and an increase in angular momentum. A rolling object on a frictionless surface will remain rotating with the same angular momentum since there is no torque causing it to stop rotating.
• Any external force (for instance from the plunger) leads to a change in angular momentum.	• An external force directed at the center of an object does not produce a torque or a change in angular momentum. A force acting tangentially on the edge of the object does produce a torque and a change in angular momentum.

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 have experience graphing quantities, including center of mass speed, for situations that include multiple steps, so that they can determine when values change, when they are constant, and the shape of curves, when appropriate.

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

- The new AP Physics 1 Student Workbook contains many helpful scenarios that specifically address the skills surrounding graphs. These scenarios can be modified or scaffolded as needed to meet student needs.
- Teachers can find useful resources in the Course Audit webpage and on the AP Central Home Page for AP Physics 1. In addition, topic questions that are tied to specific learning objectives and science practices can be found on the new AP Classroom.
- The AP Physics Online Teacher Community is active and there are many discussions concerning teaching tips, techniques, and activities that many 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 Advanced Placement Summer Institute (APSI). An APSI is a great way to get in-depth teaching knowledge about the AP Physics curriculum and exam, and is also a great way to network with colleagues from around the country.

Question #2 **Task:** Qualitative, quantitative, translations **Topic:** Modified Atwood machine

Max. Points: 12 **Mean Score:** 4.65

What were the responses to this question expected to demonstrate?

In this problem students are asked to describe the limiting case behavior of a modified Atwood machine: a mass on a table connected across a pulley to a hanging mass. To successfully complete the problem, they must demonstrate understanding of the following concepts:

- The hanging mass will exert a force to accelerate the entire mass of the two-body system. A hanging mass much smaller than the mass on the surface corresponds to a very small force acting on a large total mass and therefore very small acceleration. A hanging mass much larger than the mass on the surface will essentially be in free fall, with an acceleration close to *g*.
- Free body diagrams can be drawn, indicating the type and direction of forces acting on each mass. This demonstrates skill in producing a common, pictorial representation of forces.
- Newton's second law can be applied to each block or the entire system to determine the acceleration of the blocks, requiring that students demonstrate skill in writing mathematical equations representing physical laws, and then manipulating those equations.
- Limiting cases for the derived equation (in this case when $m_B >> m_A$) should be consistent with the qualitative estimate in part (a). This requires mathematical reasoning.
- Including a non-negligible mass of the pulley leads to a smaller acceleration which can be used to determine the change in tension in the vertical part of the string using the free body diagram from part (b).

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 often able to indicate a qualitative understanding of the acceleration of the system when one mass is significantly larger than the other.

- Students performed well in representing the forces acting on an object by using a free body diagram. Students typically attempted to use Newton's second law as the correct starting point for the derivation for acceleration, though often did not clearly apply $F = ma$ to each of the two blocks or to the entire system without internal forces. Students who successfully started this derivation were typically able to carry out the mathematical manipulation necessary to complete the problem.

- Many students attempted to use their equation to show consistency with their qualitative answer in part (a)ii, though a number of students used physical rather than mathematical reasoning, essentially restating their reasoning from part (a)ii without using their equation to show consistency.

- Very few students were able to successfully explain how including a massive pulley would affect the tension in the string, even in cases where the correct check box was selected.

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

- Some students incorrectly indicated that the acceleration would always be equal to the acceleration due to gravity, either because there was a mass falling vertically or because the surface was frictionless, not recognizing that the hanging mass must accelerate both masses. A smaller number of students incorrectly conflated acceleration with speed, indicating that the masses in part (a)i would move with a slow speed rather than a small acceleration.

- Many students incorrectly wrote a single equation for Newton's second law in part (c) that included factors such as tension, friction, and some combination of the masses in an attempt to determine the acceleration. In this case, they did not recognize that they must write F = ma separately for each object, or that a system equation requires the net, external force and only drives the entire, combined mass.

- Many students incorrectly assumed that the tension must always be equal to the weight of the hanging block, not recognizing that the block's non-zero acceleration means that forces must be unbalanced.

- Some students did not realize they should both demonstrate mathematical reasoning and make a comparison to their earlier estimate in part (d).

  In part (e) most students provided an incorrect general statement, such as more mass means there is more tension or that the tension is unaffected if the pulley spins with negligible friction, or a general statement that did not prove the result, such as a massive pulley provides resistance that increases the tension. Some used an argument that a larger tension (essentially a larger mass) would be needed to accelerate the system at the same rate (not answering the question asked). Others included incorrect statements that the tension in a string is always the same or made arguments that suggested the string now had mass. Few identified that the acceleration decreased.

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• A mass falling vertically will always fall with acceleration 9.8 m/s^2. The mass resting on the frictionless surface has no effect and does not factor in to the acceleration of the system.	• A mass connected to a string may have a force of tension acting on it and the net force leads to an acceleration of the total mass of the system. Example: The hanging mass must pull both masses, so if A is much heavier, the small force due to the mass of B means that A will have an acceleration that is practically zero.
• A system is described by a Newton's second law equation that should include the weights of both masses and tension in the string.	• Newton's second law is applied to each mass using the free body diagram drawn in part (b).
• The tension in a rope supporting an object is always equal to that object's weight.	• When an object experiences acceleration, the forces on that object must be unbalanced; thus, the tension in a rope supporting an object is only equal to the object's weight in the equilibrium case. Example: For the hanging mass, mg – T = ma.
• It is sufficient to state that the equation agrees with earlier	• Taking a limiting case of an equation provides a specific prediction that can be

reasoning without providing evidence.	compared directly to an earlier physical estimate. For example: In my equation, if m_A is much less than m_B, the denominator $m_A + m_B$ is basically equal to m_B, which cancels with the m_B in the numerator leaving $a = g$, which is what I said in part (a).
• Either a massive pulley simply leads to a larger tension because it adds resistance, or has no effect because it rotates without friction or it is the same string.	• A massive pulley adds inertia to the system which leads to a lower acceleration. Using the free body diagram for the hanging block, a lower acceleration must occur due to an increase in tension, making the forces on the hanging block less unbalanced.

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?

- Give students experience using limiting case reasoning. After completing an assignment, encourage students to ask limiting case style questions: what would happen if the incline were 0°? 90°? What happens in the circuit if the resistor were very large? Very small? These questions can be asked as follow-ups to virtually any typically assigned textbook problem or experiment in AP Physics 2.

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

- The new AP Physics 1 Student Workbook contains many helpful scenarios that specifically address the skills surrounding limiting case analysis. These scenarios can be modified or scaffolded to meet student needs.

- Teachers can find useful resources in the Course Audit webpage and on the AP Central Home Page for AP Physics 1. In addition, topic questions that are tied to specific learning objectives and science practices can be found on the new AP Classroom.

- The AP Physics Online Teacher Community is active and there are many discussions concerning teaching tips, techniques, and activities that many 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:** Experimental design **Topic:** Hooke's law

Max. Points: 12 **Mean Score:** 5.38

What were the responses to this question expected to demonstrate?

Students designed an experimental investigation of a spring-mass system using a launcher. They were to determine if the spring constant of a spring changes with compression distance. Student responses were expected to:

- Connect a physics principle to a mathematical expression for spring constant in terms of measurable values. In their response, students should demonstrate understanding of the concept of conservation of energy as applied to a spring-mass system—that the potential energy stored in the compressed spring-mass system would be converted to kinetic energy of the launched sphere, and that this could be expressed mathematically to determine the spring constant.

- Show that they could design an experiment that would measure relevant values to be used in their calculations for the spring-mass system. This involved predicting what would happen upon launching the sphere, having a good comprehension of what quantities are measurable in a lab setting, and knowing what equipment would be used to make those measurements. This also required students to minimize uncertainty in their experimental design.

- Describe how the data could be used to confirm the hypothesis. They needed to know to compare values at multiple compression distances; this includes recognizing that there would be unavoidable experimental uncertainty and they should therefore not expect their calculated values to be exactly equal.

- Sketch a graph that showed the relationship between the mass of the sphere and the launch speed. To do this, they must realize that launch speed and mass are inversely related, either though conceptual understanding or by referencing their math earlier in the problem, and correctly graph an inverse relationship.

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?

This question targeted conservation of energy, a fundamental concept in physics. At its core, this problem was a straightforward spring-mass energy problem. Most of the responses correctly approached the problem using an energy method.

- In the algebra at the beginning of the problem, those students who recognized that energy conservation was the right way to analyze the spring-mass launcher generally did well. Many students did not look to conservation of energy as their physics principle, often starting with Newton's 2nd Law, Hooke's Law, or simple harmonic motion instead. This would then lead to an algebraic expression that, while mathematically correct, would not form the basis of a proper experiment with a launched sphere.

- The algebra requirement in part (a) was minimal, only asking students to rearrange an energy expression to solve for k.

- In designing the experiment, the responses varied widely. There are a variety of ways to set up this investigation. The most common experiment was to fire the launcher horizontally and measure the exit velocity of the sphere. Other common methods involved launching the sphere straight up and measuring the maximum height or launching the sphere horizontally off of a table and using projectile motion to determine the launch speed. While most students had a general plan to set up one of these investigations, they often provided responses that were too vague, measured the wrong quantities, or did not demonstrate an understanding of proper laboratory measurement techniques. Most knew which equipment should be used to measure distances, times, and velocities.

- Those students who approached the situation with forces or simple harmonic motion often ignored the instructions in the problem to launch the sphere. Those that still designed an experiment where the sphere was launched often did not realize why their measured values would not work in their Newton's Law or simple harmonic motion equations.
- In part (c) students had to explain how to determine whether their data would confirm the hypothesis. Most knew that simply finding spring constants at multiple compression distances and comparing them would work. Very few indicated that there would be variation in those values due to experimental uncertainty.
- In the graph, most students concluded that an increase in mass would result in a decrease in launch velocity. Many students did not realize that the shape of an inverse relationship on a graph would be concave up. It was very common for students to draw a linearly decreasing 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*
• Using quantities in their mathematical expression that cannot be measured in a lab, such as potential energy. $k= 2U^2/x^2$	• Using only measurable quantities $k = mv^2/x^2$
• Failure to understand that the force from the spring changes as its compression changes. Example: Measure compression distance. Launch the sphere and measure the force applied during launch with a force meter.	• Avoid using force and Hooke's Law as the method to find spring constant. Use conservation of energy. Example: Measure compression distance. Launch the sphere and measure exit speed. Use that to determine the spring constant.
• Measuring the force applied to the sphere by the spring sometime after the spring left the launcher.	• Measuring the force applied to the sphere by the spring while the spring is still at rest at one of the marked positions with the pin removed.

• Students often did not know what measured values corresponded to the variables in their mathematical expression. Example: When launching the spring, to calculate the spring constant using $\frac{1}{2}mv^2 = \frac{1}{2}kx^2$, a student might measure the speed when the sphere hits the ground or fail to recognize that the x in the equation is the compression distance of the spring. Often students were vague and did not express what distances or speeds they measured.	• Better response: measure the compression distance of the spring with a meterstick. Use a motion detector to measure the speed of the sphere as it exits the launcher. Measure the mass of the sphere. • Alternate response: Measure the mass of the sphere. Measure the compression distance of the spring with a meterstick. Launch the sphere toward a wall one meter away. Measure the time for the sphere to hit the wall. Divide distance by time to get the exit speed of the sphere.
• Students wanted to use digital measuring tools in their experiment, but did not know what they were or how to use them. Examples: Aim a force meter at the sphere, use a speedometer to measure speed.	• Use a motion sensor to measure speed. Push the spring using a force meter to measure force at maximum compression.
• Failure to recognize that there will be unavoidable variation in answers due to experimental uncertainty. Example: Measure the sphere's launch velocity once for each pin position. Example: If my calculated k values are all the same, then the hypothesis is confirmed.	• Better response: If my calculated k values are all close enough to be within acceptable experimental uncertainty, then the hypothesis is confirmed Example: Measure the sphere's launch velocity several times for each compression position. • Better response: If I graph v^2 vs x^x and my line of best fit is linear, then the hypothesis is confirmed.
• Failure to understand the shape of the graph of an inverse relationship Example: Drawing a linear graph with a constant downward slope.	Correct response: Curve that is decreasing but concave up.

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?

- Show problems where a spring-mass system is best approached with energy methods and why Hooke's Law and forces are not appropriate in those cases.

- Make sure that students are doing experiments where they do some or all of the design and set up. Students should understand how their measurements fit into their calculations. Avoid "cookbook" labs where students just make measurements as instructed and put them in pre-determined calculations.

- Emphasize uncertainty in labs. Don't just tell students to write "perform it multiple times." Let them realize that uncertainty is inevitable and show them how we address it with error analysis, lines of bit fit, multiple trials, etc.

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

- The new AP Physics 1 Student Workbook contains many helpful scenarios that specifically address the skills surrounding designing laboratory experiments. These scenarios can be modified or scaffolded to meet student needs.

- Teachers can find useful resources in the Course Audit webpage and on the AP Central Home Page for AP Physics 1. In addition, topic questions that are tied to specific learning objectives and science practices can be found on the new AP Classroom.

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Question #4 **Task:** Paragraph question **Topic :** Power, energy, circuits

Max. Points: 7 **Mean Score:** 2.08

What were the responses to this question expected to demonstrate?

Students were provided a diagram of an electrical circuit with a resistor and a motor, with the motor lifting a block. The problem states that the power of the motor is related to the voltage drop in the motor. Students were asked to demonstrate the following.

- Determine an expression for mechanical power using given variables. This required an understanding of energy and power, recognizing that the work done in lifting the block is equal to MgH and that this quantity divided by time is the desired power.

- Explain, in paragraph form, how they would add another resistor to the circuit to decrease the time it took for the motor to lift the block. Students must recognize that lifting the block in a shorter time implies a greater power in the motor, meaning there must be a larger voltage drop in the motor. There were two common approaches to this. In one, the students explained that adding a resistor in parallel to R_1 would decrease the effective resistance of the circuit. This increases the current in the circuit, thus increasing the current in the motor, and by V=IR increases the voltage drop in the motor. In the other approach, students saw that adding a resistor in parallel to R_1 would decrease the resistance of that section of the circuit, which would cause a smaller voltage drop across R_1, meaning there would be a larger voltage drop across the motor according to Kirchoff's Loop Rule. Students had to relate the increase in power or voltage drop of the motor to a shorter time to lift the block.

- In addition to showing understanding of how changes in the resistor arrangement would cause changes in current and voltage drop in the circuit, students had to provide an explanation in a logical, sequential and coherent format that eventually reached a result that indicated a decreased time to lift the block.

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?

- Among the students who recognized that the first part of the question was strictly based on mechanics, many were able to find a correct expression for power, $MgH/\Delta t$. A large number of students couldn't see past the circuit and tried to incorporate current and voltage. Others only made seemingly random arrangements of the provided variables, despite the fact that the equation $P=\Delta E/\Delta t$ is provided on the equation sheet with the exam.

- In the paragraph, most students were not able to put all the pieces together and figure out how adding a parallel section to the circuit would cause an increase in the voltage drop of the motor. For many students, their understanding of circuits seemed limited to basic claims about the behavior of series or parallel circuits. In these cases, details about adding a new resistor combination to an existing circuit were confusing. In particular, students often had trouble distinguishing the voltage drop and current in the motor from vague voltage and current terms that seemed to apply to the circuit as a whole.

- Most of the responses had errors in logic and/or understanding or were written using statements that did not follow in a coherent manner. It was difficult for students to earn the point for a logical, relevant, and internally consistent argument. Often, students would spend most of their response justifying or solving for the effective resistance, and spend little time or effort on the other parts of their argument.

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 did not understand that there is an inverse relationship between power and time	• In order to decrease the time Δt to lift the mass, the power of the motor must increase, as shown by $P=\Delta E/\Delta t$.
• Students do not recognize that g is a physical constant when finding an expression for power in terms of M, H, Δt, and physical constants. One of the most frequent responses we saw was $P = MH/\Delta t$.	• $P = MgH/\Delta t$
• The time to lift the mass can be found using $I = \Delta q/\Delta t$ Example: if the current in the circuit is increased, the time will be decreased because $I = \Delta q/\Delta t$ Students also view current as the speed charges get to the motor, stating that if the current decreases then charges get to the motor more slowly, making it run slower.	• The time to lift the block is inversely related to power. Power is related to voltage drop, as stated in the question. Therefore, an increase in voltage drop in the motor will increase the power of the motor and then decrease the time Δt.
• Students don't recognize that the total voltage drop across the resistor/motor circuit must add up to the voltage of the battery. Example: According to $V=IR$, if R increases then V increases. If you put the resistors in series, the total R gets larger so V gets larger.	• Better analysis using Kirchoff's Loop Rule: the total ΔV for the circuit equals the voltage of the battery. By adding a resistor in parallel to R1, the parallel section of the circuit has a lower effective resistance, and therefore has a smaller ΔV than before. That means that the ΔV across the motor is larger.
• Students think current is constant in a circuit. Example: when you add a resistor in parallel, the effective resistance goes down. Since the current is constant, that makes the voltage drop go down.	• When you add a resistor in parallel to another resistor, the effective resistance of the circuit goes down. This causes an increase in current through the circuit.

• Students make only vague general statements about the circuit without being specific about the motor. Example: If the current goes up then voltage goes up.	• If the current increases in the circuit, then since the motor is in series with the parallel combination, the current in the motor will also go up. • If the current increases in the circuit, then it also increases in the motor. By $\Delta V=IR$ if the current in the motor increases then the voltage drop across the motor also increases.

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?

- Make sure that students understand circuits conceptually, not just numerically. Students should not have to make up numbers and solve the problem numerically to know that the effective resistance of a parallel circuit is smaller than the resistance of any individual resistor in the parallel arrangement.

- Don't rely on memory tricks and memorized rules about series and parallel arrangements. Discuss changes in circuits. Emphasize how voltage and current change throughout the entire circuit when you change the arrangement of resistors anywhere in the circuit. Do circuit labs where students can make changes in a circuit and see how those changes impact other parts in the circuit.

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

- The new AP Physics 1 Student Workbook contains many helpful scenarios that specifically address circuits conceptually. These scenarios can be modified or scaffolded to meet student needs.

- Teachers can find useful resources in the Course Audit webpage and on the AP Central Home Page for AP Physics 1. In addition, topic questions that are tied to specific learning objectives and science practices can be found on the new AP Classroom.

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

Question #5 **Task:** Other **Topic:** Waves

Max. Points: 7 **Mean Score:** 2.62

What were the responses to this question expected to demonstrate?

Students were asked to demonstrate the following:

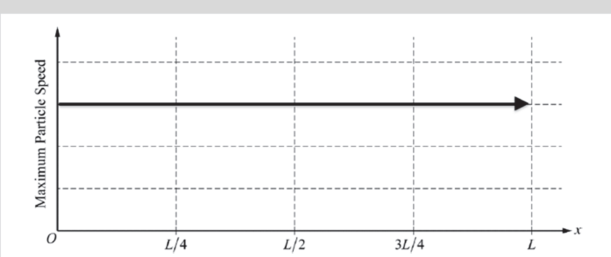
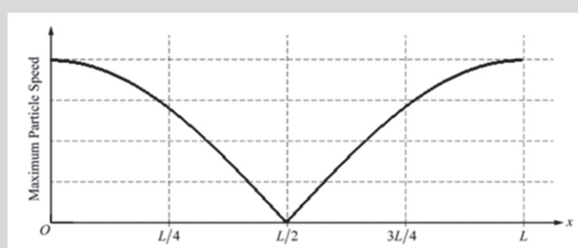
- An understanding of the resonant frequencies of tubes open at both ends and open at one end.
- Use of the mathematical relationship between frequency and wavelength.
- Use of the mathematical relationship between length of the tube and wavelength.
- Understanding where nodes and antinodes exist in a tube as well as the peak speed of particles at nodes and antinodes.

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?

- Most students correctly related velocity, frequency, and wavelength.
- Many students showed experience in relating resonant frequency and tube length.
- Students typically recognized that the graph of maximum particle speed is symmetric about L/2.
- Students often did not write the fundamental frequency equation before beginning calculation.
- Most students correctly included units.

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

- Students often confused wavelength and tube length.
- Students confused wave speed and particle speed.
- Some students mixed up the two types of tubes.
- Students attempted to use memorized results that were inaccurate.
- Students often assumed that wavelength or frequency remained the same, or thought that L could change in part c. Student did not solve for the requested quantity in the prompt.

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Confusing wavelength and tube length: L = 340/512	• λ = 340/512
• Incorrectly confusing wave speed and particle speed: 	• 

• Incorrect relationship between tube length and wavelength (such as open-open for part (c)): $\lambda = 2L$	• f = 1005/ 4L
Incorrect mathematic relationship: • f = 2L/340 • f = 1005/0.33	• f = 340/2L • f = 1005/ (4 • 0.33)
• Solving for a quantity not requested and assuming frequency remains fixed. $\lambda = 1005/512$	• f = 1005 / (4 • 0.33)

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?

- Have students start from a fundamental equation and show substitutions for a calculation. Use equations from the equation sheet as a starting point.
- Give students experience creating novel graphs.
- Insist that students include units on final answers.
- Emphasize the difference between the two types of tubes and the location of nodes and antinodes in each type.
- Take time to make graphs precise.
- Pay attention to what is suppose to be calculated or graphed.
- Give students a variety of hands-on experience.

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

- The new AP Physics 1 Student Workbook contains many helpful scenarios that specifically address the skills surrounding graphing, as well as the concepts covered in unit 10 of the curriculum framework. These scenarios can be modified or scaffolded to meet student needs.

- Teachers can find useful resources in the Course Audit webpage and on the AP Central Home Page for AP Physics 1. In addition, topic questions that are tied to specific learning objectives and science practices can be found on the new AP Classroom.

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