AP® CollegeBoard

Chief Reader Report on Student Responses:

2022 AP® Physics 1 Free-Response Questions

• Number of Students Scored	144,526			
• Number of Readers	471 (for all Physics exams)			
• Score Distribution		Exam Score	N	%At
		5	11,488	7.9
		4	24,596	17.0
		3	26,451	18.3
		2	39,141	27.1
		1	42,850	29.6
• Global Mean	2.47			

The following comments on the 2022 free-response questions for AP® Physics 1 were written by the Chief Reader, Brian Utter, Teaching Professor, University of California, Merced. They give an overview of each free-response question and of how students performed on the question, including typical student errors. General comments regarding the skills and content that students frequently have the most problems with are included. Some suggestions for improving student preparation in these areas are also provided. Teachers are encouraged to attend a College Board workshop to learn strategies for improving student performance in specific areas.

Question 1

Task: Short Answer
Topic: Force and Energy
Max Score: 7
Mean Score: 1.81

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Identify forces exerted on an object and relate the net force to the acceleration of the object.
- Describe energy transformations as a system moves to and from rest.
- Derive an equation for the displacement of a block attached to a spring using energy conservation.
- Communicate knowledge of forces and energy transformations through verbal, mathematical, and graphical forms.
- Represent energy changes using energy bar charts in a system with and without friction present.

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?

- Responses used the correct forces exerted on Block 2. Incorrect responses did not mention both forces exerted on Block 2 or mention that the forces on Block 2 were unbalanced and, therefore, created an acceleration. Other incorrect responses did not discuss only the forces exerted on Block 2. For instance, they tried to reason that the gravitational force from Block 2 was related to the spring force without mentioning the tension force in the string.
- Responses showed an understanding of initial and final force equilibrium. The phrase "derive an expression" is generally being interpreted by students correctly, and they know to start with known equations and solve for one of the variables algebraically. The majority of incorrect responses tried to solve for Δy using equations for force.
- Responses checked the correct selection "does not change" AND gave a brief explanation as reasoning. Students generally understood the system included all the objects listed in the question and focused on the definition of mechanical energy. The most common incorrect responses restated the forms of energy transformations occurring in the system as it moved from rest. The piece of the response most frequently forgotten indicated what would change the total mechanical energy in terms of external forces or friction.
- Students knew how to draw an energy bar chart and connected that having friction present would change the total amount of energy for gravitational and spring potential energies. Incorrect responses showed the gravitational energy as being zero, even though the system did not move as far with friction present. Other incorrect responses had one or both energies as negative values to indicate a decrease. Students were not comfortable having uneven values for the starting and ending energies. They did not consider that these were only two forms of energy present in the system in the final situation.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*

• Responses did not address the movement of Block 2 in terms of forces.
    o Most responses mentioned the gravitational force causing Block 2 to move down, and the tension force caused Block 2 to slow down.
    o Frequently responses incorrectly made a connection between zero velocity and
	• Responses mentioned the magnitudes of the gravitational force and the tension force on Block 2, and the net force caused the system to accelerate in the correct direction.
	• Responses stated that the net force and acceleration were in the same direction.

balanced forces by stating Block 2 would stop when the tension force equaled the gravitational force. ○ Often responses mentioned the forces exerted directly on Block 2 as the gravitational and spring forces. However, it was typical for responses not to relate the spring force to the tension force in the string. The spring pushing M_1 was another incorrect response. ○ Sometimes conservation of energy was used to analyze the motion of the system. ○ Sometimes the acceleration of the system was thought to be due to a difference in mass between M_1 and M_2.	• Responses connected the force from the spring correctly to the tension force in the string.
• Responses set gravitational force equal to the spring force to solve the distance Block 2 moved or used kinematics equations. • Responses did not use the fact that the distance Block 2 moved is the distance the spring stretches. • Responses did not label the variable for mass as M_2.	• Responses set up a system of equations for Block 1, using the spring force = tension in the string, and for Block 2, using gravitational force = tension in the string. This equilibrium point occurs at $\frac{\Delta y}{2}$. • Responses used conservation of energy with the correct substitution for the distance and correctly identified the initial energy in the system as gravitational potential and the final energy in the system as the spring potential energy. • Responses correctly labeled the mass variable as M_2 to show the system's initial energy.
• Responses restated energy conservation, or no energy loss occurred due to changing from gravitational potential to spring potential energy.	• Responses correctly state that the mechanical energy "does not change" due to no work, external forces, or Block 1 is on a frictionless surface. The responses defined a closed system or energy conservation using a force description.
• Responses drew an energy bar as a negative or zero value. • Responses did not connect that the new Δy would be smaller and result in some non-zero gravitational potential energy. • Responses ignored the instruction to represent zero energy with a line on the graph. Showing no line left the answer incomplete and incorrect.	• Responses drew the total energy of the gravitational and spring potential energy as less than four units because the final energy without friction was four units. • Responses correctly shaded the energy bars to sum to less than four units when the surface had friction.

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 students how to distinguish and identify different spring systems. They should know when to use force, energy, and period equations.
    - Do a comprehensive review of springs once all units are covered. Ask students to do practice problems involving springs in various systems and require different methods, such as a force and an energy analysis, to arrive at the final solution.
- Teach students that a system of masses can have a changing acceleration and do examples in class as well as in the lab to show this idea.
    - Example lab: Have students pull a spring with attached mass and known spring constant a distance from equilibrium. Increase the distance and have students calculate the initial acceleration of the mass attached to the spring for each distance. Plot a graph of initial acceleration vs. distance from equilibrium. The graph should show changing acceleration.
- Teach students how to solve for unknown variables algebraically in addition to numerically.
    - Introduce a topic using numerical calculations. Review and assess the topic using algebraic expressions.
- Teach students that the length of a string stays constant, so the distance an object will move horizontally on a table will equal the distance the object will move vertically off the table in this case. Discuss how variables for distance are measured in the same unit and allow students to practice these types of problems.
- Ask students to compare the downward acceleration of an object to the acceleration of an object only under the influence of the force of gravity. Then require an explanation for why the acceleration is the same, greater than, or less than using a net force statement.
- Ask students to always clearly label equations and variables with subscripts, especially when writing expressions that involve multiple objects.

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

- Teachers should direct students to AP Daily videos from the Energy and Forces units.
- Teachers should direct students to Higher Ed Faculty Lectures on Energy and Forces.
- Teachers should assign topic questions as well as personal progress check items to monitor progress being made in the mastery of content.
- Additional questions involving energy bar charts can be found in the AP Physics 1 student workbook. These scenarios help students practice using the ideas of conservation of energy and re-expressing physical phenomena with bar charts.

Question 2

Task: Qualitative-Quantitative Translation
Topic: Gravitation
Max Score: 12
Mean Score: 5.70

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Describe the gravitational forces between multiple objects of different masses and different distances from each other.
- Create appropriately labeled free-body diagrams for multiple forces exerted on a single object.
- Make a conceptual argument about gravitational interactions between objects.
- Derive an equation using Newton's second law.
- Determine consistency between reasoning based on a conceptual argument and a derived equation.

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 were able to recognize gravitational forces and relate those forces to the distance between objects.
- The responses often included accurate free-body diagrams for both moons. Commonly, responses included labeled force vectors for both the moon-planet and moon-moon gravitational interaction. There was a considerable lack of consistency within the labeling on the free body diagrams.
- Responses correctly discussed vector addition when developing a conceptual argument for the forces between the objects. Responses often also recognized the inverse relationship between the distance between objects and the gravitational force exerted on each object.
- Most responses were able to identify the law of gravitation as the fundamental equation for the start of the derivation. Most used correct forms of vector addition and most accurately substituted the masses and distances appropriately into the equation.
- A surprising number of responses had mathematical errors in their equations: dropping the square in the denominator, algebra mistakes in the numerator (e.g., $m_0 m_0 = 2m_0$), and using alternative variables (e.g., m_A instead of m_0), to state a few examples. There were a large number of expressions that added and subtracted dimensionally incompatible terms and/or resulting expressions that were not forces.
- Most students had difficulty connecting arguments from part (b) to the derived equations in part (c). In part (d), most responses successfully noted how vector addition appeared in the derived equation. However, in part (d)(ii), the majority of responses were incomplete, addressing only one of the forces on Moon B, which appeared in the part (c) equation.

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

Generally, the law of gravitation is well understood to be used when describing the forces exerted on planetary-sized objects.

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• One arrow on a free body diagram is used to represent net force.	• Each force on a free-body diagram depicts a unique interaction between objects. If multiple interactions are taking place, each interaction should have its own arrow to represent it.
• Labels on the free-body diagrams do not depict the force they represent	• Labels, such as F_{AB} and F_{APlanet}, clearly differentiate the forces on Moon A due to Moon B and the planet, as do other labels with multiple subscripts, such as F_{GB} and F_{GP}.
• Only the final line of the derivation is shown.	• Complete derivations begin with at least one equation from the provided equation sheet and then show substitutions from the list of variables appearing in the prompt.
• Poor algebraic expressions.	• Proper final equations for net force include only the variables listed in the prompt (m_0, m_p, R_A, R_B, and constants) and dimensionally appropriate addition and subtraction for force expressions.
• The translation does not fully address both qualitative and quantitative arguments.	• The highest scoring responses referenced specific arguments from the qualitative section (part (b)) and how those arguments appeared in the quantitative argument (part (c)).

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?

- It is useful to practice labeling forces of the same type but of different magnitudes. For instance, just as an object with different tensions exerted on it may include force labels, such as F_{T1} and F_{T2}, to differentiate the forces, an object with multiple gravitational forces on it can be labeled F_{g1} and F_{g2}.
- Generally, it is appropriate for all forces on a free-body diagram to be labeled as F with an appropriate subscript. For example:
  - Friction — F_f
  - Normal Force — F_N
  - Tension — F_T
  - Force of Gravity — F_g
  - Force of Gravity on Moon A due to Moon B — F_{AB}

- Derived equations should always start with a law or equation from the equation sheet. One process to encourage that would be to require that derivations contain (at least) three separate lines:
    1. a starting law or equation from the equation sheet
    2. substitution of variables and constants from the problem
    3. the algebraically manipulated final expression

  Students should practice deriving equations and be evaluated on the completeness of the derivation in addition to the final result.

- The translation section of the qualitative-quantitative translation should specifically address the parts in the derived or given equation that directly coincides with the qualitative description. For example, the most complete responses often followed this pattern: "In part (b)(ii) I reasoned … and my expression in part (c) shows." In that format, the translation section of the response is forced to address all features of an argument.

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

- Teachers should direct students to AP Daily videos from the Forces unit.
- Teachers should direct students to Higher Ed Faculty Lecture on Forces.
- Teachers should assign topic questions as well as personal progress check items to monitor progress being made in the mastery of content.
- Additional questions involving the force of gravity and the relationships between written claims and equations can be found in the AP Physics 1 student workbook. These scenarios help students practice making claims and justifying those claims with connections between qualitative and quantitative representations.

Question 3

Task: Experimental Design
Topic: Energy
Max Score: 12
Mean Score: 5.92

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Design a procedure for an experiment to measure changes in kinetic energy and gravitational potential energy, including a method to reduce experimental uncertainty.
- Identify the quantities needed to calculate changes in kinetic and potential energies, including the kinetic energy of the block immediately before it hits the floor.
- Analyze data gathered by an experimental procedure.
- Apply conservation of energy to account for the rotational kinetic energy of the wheel. Specifically, responses should indicate that because the total mechanical energy of the block-wheel-Earth system remains zero throughout the block's motion, the total energy should be zero over the full range of the graph.
- Draw a reasonable best-fit line that follows the trend suggested by the data points in the graph, includes approximately the same number of data points above and below the line, and is not forced to go through data points or the origin.
- Use the slope of the best-fit line to calculate rotational inertia.

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?

- Responses generally contained plausible lab procedures that addressed the question. Responses frequently outlined methods for measuring a change in gravitational potential energy, although some responses had difficulty describing how to find velocity.
- Responses earned the first point in part (b) very frequently, while the second point was earned less often. In many cases, the response incorrectly described how to find the block's final kinetic energy using its average velocity. Many responses argued that the block's final kinetic energy was equal to the initial potential gravitational energy in the block-Earth system, disregarding the rotational kinetic energy of the wheel.
- Responses generally included correct best-fit lines. Students were comfortable indicating the rotational kinetic energy of the wheel increased from zero, and most were able to draw their line in such a way that the total energy was zero.
- While many responses did include a reasonable line of best fit, there were also many with vertical shifts that were too high or low and slopes that were too steep or not steep enough. Students seemed to have difficulty calculating a slope and frequently used a single point from their line, even when their line of best fit had a non-zero y-intercept. Frequent errors included equating the slope to the rotational inertia and excluding correct units.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Gravitational potential energy is always fully converted to translational kinetic energy as an object moves downward. Therefore, the final velocity of a mass that is moving downward will always be $\sqrt{2g\Delta h}$.	• Students recognize the many forms of energy that can exist in a system.
• The instantaneous velocity of an accelerating object can be calculated using displacement divided by time.	• The instantaneous velocity of a moving object can be determined by reading values off of a velocity vs. time graph generated with a motion sensor, calculating the slope of a line drawn tangent to a graph of position a function of time, or calculating change in position over the time interval for a small Δt . • The final velocity of an object that uniformly accelerates from rest is twice its average velocity.
• The acceleration of any object that is moving downward is g , so the instantaneous speed of the block at any time is gt .	• The string exerts an upward tension force on the block, so the net force on the block is less than its weight. Therefore, the block's acceleration is less than g.
• The slope of a line that does not pass through the origin is the ratio of the y and x value of a single point on the line. • The slope of a best-fit line is calculated using two data points that are not on the best-fit line.	• Slope is found by calculating $\frac{\Delta y}{\Delta x}$ between two points that are on the line. Explicitly showing this calculation makes it clear how a numerical slope was calculated.
• The slope of the line of best fit is the final answer.	• In this situation $I = \frac{2\Delta K}{\omega^2}$ so the calculated rotational inertia should have a value that is twice the slope of the line.

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?

- It is important for teachers to craft their courses in such a way that students are frequently engaged in focused, open inquiry experiences. Science practices 4 and 5 describe the skills students develop as they design, conduct, and analyze the results of an experiment.
- Teachers should explore examples of experimental design questions from past tests and the question bank, as well as the sample instructional activities outlined in the course and exam description. Students should be familiar with the name and function of simple tools like meter sticks, stopwatches, and balances. Students will be more successful answering an experimental design question if significant class time is spent engaging with novel questions in creative ways.

- Students are expected to be able to compare values from graphs, calculate slopes, and calculate areas and then discuss the meaning of these calculations. To answer part (d) of this question, many students calculated a slope, yet that slope was not the final answer. Students should be asked to interpret the meaning of slopes and areas of graphs with unfamiliar axes. An effective task is to show students a pair of axes and ask them to describe the significance of a single point, a calculated slope over a range, the instantaneous slope at a point, and the area under the graph within a range.

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

- Teachers should direct students to AP Daily videos from the Energy unit.
- Teachers should direct students to Higher Ed Faculty Lecture on Energy.
- Teachers should assign topic questions as well as personal progress check items to monitor progress being made in the mastery of content.
- Additional laboratory design and data analysis questions can be found in the AP Physics 1 student workbook. These scenarios help students practice designing specific experiments to answer scientific questions and analyze data.

Question 4

Task: Paragraph-Length Response
Topic: Momentum and Collisions
Max Score: 7
Mean Score: 2.26

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Draw a vector arrow for momentum that indicates conservation of momentum in a collision.
- Apply knowledge of conservation of momentum in a collision in two different situations.
- Compare the final velocities of blocks after an elastic or inelastic collision.
- Identify the relationship between momentum and velocity.
- Indicate that the time of flight in projectile motion is independent of mass and depends only upon vertical height, which is identical for both cases.
- Indicate that in horizontal projectile motion, the initial horizontal velocity and time in the air determine the range. More generally, identify the relationship between velocity and displacement in the horizontal direction, including the fact that there is zero acceleration in the horizontal direction.

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?

- Responses generally did well in recognizing that conservation of momentum should be used but did not do well showing how conservation of momentum applied to the situation given in the prompt.
- Most responses were able to create a logical, scientific argument that earned the paragraph point in the rubric. The physics was not always correct, but most students were able to link multiple physics ideas together to try and address the posed question.
- Most responses showed a good understanding of the proportional relationship between displacement and velocity. However, the responses did not usually connect time to the other concepts. Very few responses addressed time at all.
- Responses indicated that the momentum was conserved and equal in both cases by drawing arrows of the same length.
- Responses typically successfully used the equation for conservation of momentum in the clay-block collision for Case A to show that the velocity of the block-clay system would be less after the collision. Some responses used conservation of momentum for the ball-block collision in Case B to demonstrate that Block B would have a larger velocity to compensate for the opposite (direction) momentum of the bouncy ball.
- Some responses used the center of mass argument of the block-ball system: the momentum of the center of mass of the ball and block will continue to move forward. Both collision's centers of mass will be at the same location. Block B will have to land farther than Block A to compensate for the negative velocity of the rubber ball.
- Responses recognized that both Block A and Block B start with horizontal velocity. The range will be determined by the horizontal velocity of the blocks just after collision. Most correct answers just stated that blocks are in the air for the same amount of time. Some responses showed it with equations.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• When drawing the momentum arrow in part (a), many responses would write the word "zero" and not draw an arrow at all.	• An arrow should be drawn to the right with a magnitude of two squares.
• The arrow drawing confuses either velocity with momentum or the momentum of a single object and momentum of the system, for instance, by drawing two arrows to show the momenta of both the ball and the block.	• One arrow should be drawn pointing to the right with a magnitude of two squares.
• Many responses assumed that because the rubber sphere bounced that the collision was elastic. There was no information in the prompt that specifically stated that the collision was elastic; therefore, it cannot be assumed to be elastic. • Due to the incorrect assumption of collision types, many responses thought that an energy argument could be used to justify the behavior and final velocity of the blocks.	• Block B will land on the floor at a horizontal distance from the edge of the table that is greater than d_A. This is due to conservation of momentum because momentum is conserved in any collision. • Because momentum is conserved, and the rubber ball travels in the opposite direction of the block and has the same starting momentum as the clay, the final momentum of Block B must be greater, meaning its speed is greater.
• Responses demonstrated a misconception of the meaning of conservation of momentum. The responses would incorrectly assume that because the momentum was conserved individual parts of the system could not change their velocity/momentum. • Often when responses were trying to justify the behavior of the blocks after the collision, the response would ignore the vector nature of momentum.	• As the sphere bounces off Block B, the sphere's momentum becomes negative. Because of conservation of momentum, the momentum of Block B must increase much more than Block A in order to offset the negative momentum of the sphere. Greater momentum results in greater velocity.
• Although many responses created a correct, connected argument to address the prompt, many had holes in their logic. The response might link momentum directly to displacement without a connecting idea of momentum to velocity and then velocity to displacement.	

• One of the more frequent omissions in a response was a mention of fall time for the two blocks. While many responses addressed a displacement and velocity relationship, they did not mention fall time, which makes the velocity/displacement relationship true.	• The two blocks have the same time in the air because they are identical, they fall the same distance, and they experience the same net force (gravity) and, therefore, the same acceleration. Therefore, because the two blocks have the same time in the air and Block B has a greater horizontal velocity, Block B travels a greater distance from the table because of $x = v_0 t$.
• Many responses demonstrated a misconception that if momentum was conserved, the value of momentum and velocity must be split after the collision between the block and the rubber sphere. The response would then incorrectly conclude that Block B would have less momentum/velocity because of the "momentum split."	• Due to the conservation of momentum theorem, momentum is constant within the block-rubber sphere system. After the collision, the rubber sphere's momentum is in the opposite direction of its original momentum. This makes the magnitude of the momentum of Block B greater than the magnitude of the initial momentum of the rubber sphere.
• Many responses showed a misconception about the effect of adding mass to Block A when the clay sticks to the block. Many responses mistakenly stated that by adding mass, the block would fall faster, have more momentum, or would go farther. The additional mass argument was often justified through an incorrect energy argument, such as "more potential energy with the added mass would lead to more kinetic energy during the fall."	• When the clay sticks to Block A, the momentum of the block-clay system is still in the positive direction. Because mass is added, the velocity of the system moving forward will be less than just the clay moving alone due to conservation of 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?

- When teaching conservation of momentum, teachers should go beyond only teaching types of collisions and what is conserved in each specific type. Students need to understand more about how momentum is conserved within the collisions rather than just identifying types. For instance, students can collect data using motion sensors to record velocity in a variety of collision experiments (e.g., carts colliding head-on, carts colliding and sticking, a moving cart strikes a stationary cart) and use the data to show how momentum was conserved.
- Students need to practice making logical step-by-step scientific arguments. In this particular prompt, responses needed to connect momentum to velocity, velocity to displacement, and address time. Several responses went straight from momentum to displacement, skipping several important statements. Students should use fundamental equations and reasoning to form their arguments. If the equations do not link together, then they are missing a step. One tip is to start with two seemingly unrelated concepts and have students try to connect them with equations/words/principles.
- Stress that total momentum of a system of colliding objects is conserved in a collision. Show the difference between a system of objects and individual objects with examples.
- Stress the difference between momentum and velocity.
- Help students recognize the physical meaning of the terms in an equation and how they relate. For example, in the equation $d = vt$, increasing v does not necessarily mean that d will also increase unless t stays constant.
- AP Classroom has a similar paragraph FRQ with a pumpkin and three different arrows. This question is great practice for the concepts addressed in this problem.

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

- Teachers should direct students to AP Daily videos from the Momentum unit.
- Teachers should direct students to Higher Ed Faculty Lecture on Momentum.
- Teachers should assign topic questions as well as personal progress check items to monitor progress being made in the mastery of content.
- Additional questions can be found in the AP Physics 1 student workbook. These scenarios help students practice content and skills required for success on the AP Physics 1 exam.
- The pumpkin paragraph question specifically mentioned above can be found in the AP Physics 1 Secure Exam 1 on AP Classroom.

Question 5

Task: Short Answer
Topic: Simple Harmonic Motion
Max Score: 7
Mean Score: 2.06

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Use models to analyze an oscillator and to identify the period.
- Reference the graphical relationship between velocity and a position versus time graph to make a claim.
- Manipulate equations to substitute quantities and arrive at an answer.
- Apply functional dependence to determine the new equilibrium position and the new period for the graph.
- Make connections between the graph and energy concepts.
- Use argumentation skills to justify reasoning.
- Analyze the graph and diagram to address the relationships between the types of and movement of energy in the system.
- Graph the position versus time for simple harmonic motion of a mass on a spring with changes in the spring constant.

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 struggled to rearrange the equation in part (a) correctly. There were a variety of correct methods to solve the problem, with the majority using the period of a spring equation. Rarely, students were able to use conservation of energy or the amplitude equation to correctly solve part (a).
- Part (b) required graphical interpretation. Many responses used a symmetry approach for both with a variety of descriptions (equal distance from equilibrium, equal distance from max/min). There were also some explanations using slope and derivative reasoning, which shows a strong understanding of the graphical connection between position vs. time and velocity vs. time.
- Part (c)(i) very clearly asked for the functional dependence, so responses were generally clear and focused because there was very little variation from the setup. Points for part (c)(ii) were challenging for students because of the difficulty in drawing sinusoidal functions.

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 manipulating equations to solve for unknown variables, many students start with the correct base equation but are unable to manipulate the equation to isolate the unknown variable correctly.	• Solving for the spring constant, for example, starts with $T = 2\pi\sqrt{\frac{m}{k}}$ leads to $\frac{T}{2\pi} = \sqrt{\frac{m}{k}}$ which leads to $\left(\frac{T}{2\pi}\right)^2 = \frac{m}{k}$ whose solution is $k = \frac{m}{\left(\frac{T}{2\pi}\right)^2}$.

• Not understanding the total potential energy is the sum of gravitational potential energy and spring potential energy in a vertical oscillating system. Many only cite one or the other. For example, "Since $U_s = \frac{1}{2}kx^2$ and the distance from equilibrium x is the same, total potential energy must be the same at both points."	• $U_S + U_g = U_{\text{Total}}$ and $U_{\text{Total}} + K = E_{\text{Total}}$ which is constant.
• Students confuse the meaning of slope and area when reading the graph. "The areas of the two points are the same so the velocity must be the same at those two points" or similar.	• The slopes of the tangent lines at both times are the same, so the velocities are the same. Because velocity is the same the kinetic energy is the same at both locations.
• The responses identified symmetry of the graph but were unable to explain the significance of the symmetry clearly or completely. For instance, students state that the graph repeats or that simply because the graph is symmetric, the energies must be the same.	• The kinetic energy or potential energy is the same at both of these times because the distance from the equilibrium line is the same.
• There were a lot of responses in (c)(i) where students found the new stretch instead of the new equilibrium. This was indicated by labeling the equilibrium position on the graph using the incomplete answer $\Delta x = 0.1$ m.	• The new stretch length is $\Delta x = 0.1$ m; therefore, the new equilibrium location is 0.9 m or 90 cm.
• When discussing distances, students often misuse the terms height, amplitude, and displacement.	• The two points have the same magnitude of displacement.
• Energy applications on part (a) were rarely done correctly. The responses again propagated incorrect conservation ideas, such as $\frac{1}{2}kx^2 = \frac{1}{2}mv^2$.	• Because kinetic energy is the same at the given locations (or max and min) $\frac{1}{2}kx_1^2 + \frac{1}{2}mv_1^2 = \frac{1}{2}kx_2^2 + \frac{1}{2}mv_2^2$.

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 with the students the basics associated with taking the test, including:
  - Be careful about writing work/answers in sections or areas not specifically designated for the response. Avoid doing so if possible. If necessary, indicate clearly where the work is continued.
  - Use the clearest, appropriately sized handwriting … what cannot be read cannot be scored.
  - Understand that free-response answers will be scanned in black and white before scoring, so it is not effective to use different colors of pens or pencil vs. pen to distinguish two curves on a plot.
- Make sure students understand common physics terms and how to appropriately use them, such as displacement vs. distance, amplitude, height, x-axis/equilibrium position, and origin.

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

- Teachers should direct students to AP Daily videos from the Energy and Oscillation units.
- Teachers should direct students to Higher Ed Faculty Lectures on Energy and Simple Harmonic Motion.
- Teachers should assign topic questions as well as personal progress check items to monitor progress being made in the mastery of content.
- Additional questions can be found in the AP Physics 1 student workbook. These scenarios help students practice content and skills required for success on the AP Physics 1 exam.