Chief Reader Report on Student Responses:

2018 AP® Physics 1 Free-Response Questions

- Number of Students Scored 170,653
- Number of Readers 380 (for all Physics exams
- Score Distribution

Exam Score	N	%At
5	9,727	5.7
4	26,049	15.3
3	33,478	19.6
2	48,804	28.6
1	52,595	30.8

- Global Mean 2.36

The following comments on the 2018 free-response questions for AP® Physics 1 were written by the Chief Reader, Shannon Willoughby, Montana State University. They give an overview of each free-response question and of how students performed on the question, including typical student errors. General comments regarding the skills and content that students frequently have the most problems with are included. Some suggestions for improving student preparation in these areas are also provided. Teachers are encouraged to attend a College Board workshop to learn strategies for improving student performance in specific areas.

Question #1 **Task:** Short Answer **Topic:** Gravitation and Forces - 2B.1.1, 2.B.2.1, 3.A.1.1, 3.A.2.1, 3.B.1.3, 3.B.2.1, and 3.C.1.2

Max. Points: 7 **Mean Score:** 2.17

What were the responses to this question expected to demonstrate?

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

- The ability to construct free-body diagrams, only including the relevant forces without extraneous forces.
- Recognition of cases in which the net force is centripetal in the context of universal gravitation.
- An understanding of how changing one quantity in an equation may or may not affect other quantities.
- Recognition that direct and inverse relationships only hold when other variables are kept constant.

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?

- Students typically understood that a center-seeking force was exerted on the spacecraft.
- Students often included velocity and acceleration vectors to the force diagram when only force vectors were appropriate.
- Students generally recognized that changing one variable in an equation will affect another variable in the equation when all other variables are held constant, and whether the change in the first variable caused an increase or decrease with the other variable under consideration.
- Students typically understood that a "derive" prompt required algebraic manipulation of 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*
• Students indicated that an orbiting object experiences a tangential force with regards to the direction of the object's motion, that the object experiences an outward directed force, or that the gravitational force exerted on the spacecraft is directed down toward the bottom of the page.	• The correct response indicates a single arrow drawn on the force diagram that is directed toward center of the planet with the arrow labelled as the gravitational force.
• Students indicated that a tangential force (such as thrust, momentum, velocity) is required to maintain circular motion.	• The correct response indicates that the only force necessary to keep the spacecraft in orbit around the planet is the gravitational force that is exerted on the spacecraft and is directed toward the center of mass of the planet.

• Students indicated that mass is irrelevant in space and that there is no gravitation in space. • Students indentified a “centripetal force” as a specific force rather than as the net center-seeking force.	• The correct response indicates that the gravitational force between the planet and the spacecraft is responsible for the inward pulling force that is exerted on the spacecraft.
• The Students indicated that the term "period" is only applicable to cases of simple harmonic motion.	• The correct response correctly solves for the time it takes for the satellite to complete one revolution around the planet.

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:

- Emphasize that when observing the relationships among variables, the effect of a change on all variables should be considered. Students should use the selected equation so that all variables are constant except for the two that are considered.
- Avoid referring to "gravity," but should instead refer to "gravitational force" or "acceleration due to gravity." Students should
- Frequently apply Newton's second law when problem-solving, including in cases of circular motion.
- Work with equations in variable forms and link equations together by their common variable(s).
- Gain extensive experience drawing force diagrams throughout the year.

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

- Teachers of AP Physics 1 can find useful resources in the Course Audit webpage and on the AP Central Home Page for AP Physics 1. Multiple Representations of Knowledge: Mechanics and Energy, the downloadable AP Physics 1 and AP Physics 2 lab manual may provide practical application of these concepts, and the downloadable reference guide for students, Quantitative Skills in the AP Sciences, may also prove to be helpful.

- 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: Experimental Design

Max. Points: 12

Topic: Resistivity - 1.E.2.1, 5.B.9.2, 5.B.9.3, 5.C.3.2, and 5.C.3.3

Mean Score: 4.57

What were the responses to this question expected to demonstrate?

- The ability to choose what quantities should be graphed so that the slope of the line will allow the unknown quantity to be found.
- The ability to correctly label axes of a graph with units.
- The ability to choose an appropriate linear scale for the axes of a graph.
- The ability to calculate the slope of the best-fit line using points on the line and not the data points that were individually plotted using a collection of data.
- The ability to convey knowledge about the intrinsic nature of resistivity.
- The ability to design an experiment with appropriate controls, identify variables and how to manipulate the variables in a physical setting with appropriate equipment, and to collect the necessary measurements in order to calculate the desired quantity/quantities.

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?

The responses could be broken into two categories: Students who had received instruction on resistivity and those who had not. Parts (a) and (b) did not necessarily require a knowledge of resistivity to complete. Students who had not been exposed to resistivity were less likely to think through the item and successfully complete the required tasks.

A common mistake for many students was using input data from the table instead of graphed data to calculate the slope of the line of best fit. For part (c), the concept of a physical property was not understood. For the majority of students who stated that shape had no effect on resistivity, they tried to explain it by manipulating the resistance equation and using the manipulation to support the flawed thought process. For part (d), a common incorrect response was that resistance could be measured directly in a circuit connected to power supply. Students did not understand that current needed to be measured in conjunction with the voltage.

Students also frequently left out the method of accomplishing a task. For example, they said to “heat the dough” or “find the current” but neglected to say how one would accomplish each task.

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 displayed a misuse of common electrical measuring tools, as well as incorrectly identifying the measuring tools by name; i.e. ammeters, voltmeters, and ohmmeters.	• Ammeters are used to measure current, and the student only needs one of these to be in series with the resistor (dough). • Voltmeters are used to measure voltage and the device needs to be in parallel with the resistor (dough).

	• Ohmmeters are used to measure resistance and the device needs to be in parallel with the resistor (dough). • An ohmmeter can only be used to measure resistance when there is no potential difference applied to the object. • A correctly drawn closed circuit; a battery of known voltage, dough as the resistor, voltmeter in parallel with the dough, and the ammeter in series with no need for additional resistors including light-bulbs.
• Students referred to poor heating or cooling methods for changing the temperature of the dough.	• An immersive heating/cooling system must be used for uniform heating/cooling of objects; i.e. an oven, a refrigerator, etc., for a period of time. • Dough placed in a sealed container before water bath submersion. • Dough placed in a metallic or ceramic container before placing the dough a distance above any open flame, so not to burn/melt the dough and to distribute heat evenly. • Dough placed in a series circuit and allowing the current flowing through the dough to warm the dough.
• Students provide poorly drawn lines of best fit.	• A ruler was used to construct a line showing equal displacement of the data points above and below the line. • Graphical analysis of a scatter plot with linear dependence reflecting a properly weighted average that considers the possibility of outliers. • A best-fit line shifted closer to the three points and farther from the outlier as to not merely connect the first and last points. • Scale and size of the graph includes the accuracy of data points to the hundredth of a decimal (for the data - 0.01 to 0.06 Ωm^2) and smaller increments are irrelevant. • Data points are distributed over half of the graph that uses consistent scales. • The data does not assume a zero y-intercept.

• Students did not express the difference between measured variables and calculated variables within an experimental investigation.	• Resistance or current and voltage <u>measured</u> (not "record," "test," or "determine") of the dough resistor to calculate resistance with Ohm's Law. The calculated resistance and controlled variables are used to calculate resistivity.
• Students confused resistance with resistivity.	• Resistance is partially determined by resistivity, but resistivity is not determined by resistance. • Resistivity is a function of the property of the material (intrinsic properties). • Since the material used in the experiment did not change, the resistivity did not change. • Changing the length or cross-sectional area of the dough would change the resistance, but the resistivity would not change.
• Students should not have assumed that testing for the response of one variable to an experiment means that other variables remained the same.	• Defining characteristics in specific terms instead of general. "Similar" does not mean the "same."

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?

Provide a checklist for describing a lab procedure that includes:

- Identification of the independent variable and how it will be changed from trial to trial, including equipment that is needed to conduct the experiment.
- Identification of the dependent variable to be measured, including the equipment and process used to measure the dependent variable.
- A description of variables that should be held constant from trial to trial.
- A description of what will be calculated with the measured data collected from the experiment.

Provide a data analysis checklist that includes:

- Choosing what quantities to graph so that the slope of the line of best fit will allow the unknown quantity to be found.
- Correctly labeling axes with units.
- Choosing an appropriate linear scale.
- Calculating the slope of the best fit line using points on the line, and not data points found in a collection of data.

Other graphing tips:

- Understand that graphs generally require a line of best fit. Students need to clearly know what that means, and that the line will, in turn, have a slope that should always be calculated regardless of whether the problem states it directly or not.
- If a calculator is used to determine the equation of a line of best-fit, then the words, "Linear Regression from Calculator" should be included in the response. This enables AP Readers to more readily award credit for supporting work that leads to a proper slope value.
- Attempt to expose your students to lab activities that will result in a non-zero y-intercept in the data analysis portion of the activity. This will enable more students to appreciate that slope is a change in y data divided by a change in x data rather than commonly incorrect use of simply using y value divided by x value.

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 on the AP Central Home Page for AP Physics 1. The downloadable AP Physics 1 and AP Physics 2 lab manual may provide practical application of these concepts, and the downloadable reference guide for students, Quantitative Skills in the AP Sciences, may also prove to be helpful.

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Question #3

Task: Qualitative/Quantitative Translation

Max. Points: 12

Topic: Torque and Rotation - 3.A.1.1, 3.A.3.1, 3.F.1.1, 3.F.2.1, 4.D.1.1, 4.D.2.1, and 4.D.3.1

Mean Score: 6.06

What were the responses to this question expected to demonstrate?

- An understanding of motion graphs, both angular velocity and angular acceleration, for a rotating object as it slows down.
- The ability to relate torque, angular acceleration, and rotational inertia in the rotational form of Newton's second law or, alternatively, the same relationship expressed by connecting angular momentum and angular impulse.
- The ability to show how motion graphs would change under the condition of a nonconstant net torque.
- An understanding of general mathematical rules as they relate to physical behavior by recognizing where a time variable must appear in an equation to match the described behavior within a graph.

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?

The responses to this question showed the following:

- Part (a) showed that students have a general comprehension of basic motion graphs for constant negative acceleration.

- Part (b) required an algebraic derivation. Students had to incorporate the rotational form of Newton's second law and torque with angular kinematics. These equations are present on the equation sheet provided. Students had some difficulty with the algebra, and often neglected to include the specific variables provided in the question stem.
  - Students were often more successful with the alternate solution that used the connection between angular momentum and angular impulse. These equations are also provided on the equation sheet. This approach allowed a very direct and possibly quicker algebraic path to the solution.

- Part (c) required students to think about the way that the graphs would change if the frictional torque were reduced. This was a demanding question, as it deviated from a typical textbook problem; students were required to apply basic skills to an unfamiliar situation. Students had to recognize a change in slope and curvature of the velocity graph, and also a change in slope of the acceleration graph. This was a significant challenge for students who often came up with individual parts of the solution but rarely put together a completely correct response.

- Part (d) asked students to choose an equation from two given choices based on a described behavior. They had to recognize that a time variable in the denominator of an equation means that the result of that equation would become smaller with time. Many students clearly had no experience with this type of problem as they focused on other parts of the equation, such as the constants or the particular variables used, and missed the intent of the question.

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 incorrectly drew basic graphs of motion with constant acceleration.	• The velocity vs. time graph in part (a) is drawn as a straight line of a negative, constant slope starting at the correct initial value of angular velocity and ending at an angular velocity of zero. The acceleration vs. time graph in part (a) is drawn as a straight, horizontal line of constant slope that is below the x axis.
• Students incorrectly drew more complex motion graphs that indicate a changing acceleration.	• After the oil is applied to the axle, the velocity vs. time graph in part (b) is drawn as a curved line of a negative, changing slope that becomes less steep as time increases. After the oil is applied to the axle, the acceleration vs. time graph in part (b) is drawn as a straight line of a positive, constant slope that is below the x axis.
• Students incorrectly derived an equation in terms of given variables, including knowing when to simplify the result by eliminating quantities that are defined as zero in the problem.	• Part (b) asked students to derive an expression for rotational inertia in terms of ω_o, τ_o, and t_1. There were equations given on the equation sheet that are useful, but students need to use proper notation and state the answer is in terms of given variables such as $I = \tau_o t_1 / \omega_o$.
• Students did not have a complete understanding of a changing acceleration in graphical form. Students often could reason out that the acceleration would change when applying oil, but could not determine how to translate their understandingto a graph.	• Part (c) required the students to draw a graph of angular velocity vs. time and angular acceleration vs. time when the friction between the disk and the axle was decreasing. The angular velocity graph should have been curved and concave upward, showing continuous change in acceleration. The angular acceleration graph should have sloped upward.
• Students had trouble looking at an equation and determining the functional dependence of variables with each other. Instead of seeing the relationship between torque and time in the equation, they either focused on the constants (e.g. "the constant should be multiplied") or tried to relate the given equation to one of the equations from the equation sheet (e.g. "I chose the second equation because it has time in the denominator like $\tau = \Delta L/\Delta t$").	• In part (d), students should be able to describe the functional dependence between time and torque in the provided equation choices. They should be able to explain that time in the denominator of the second equation means that torque will decrease as time passes, as was explained in the question stem.

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:

- Practice graphing with their students, in both translational and rotational situations. Graphing exercises should extend to situations with changing acceleration. Teachers should encourage students to use straight-edges to construct straight lines.
- Provide students with more practice using first principles to derive new equations in a multi-step algebraic process. Emphasize communicating mathematics in a step-by-step manner rather than jumping directly to the solution.
- Demonstrate various ways to approach a situation from first principles, such as Newton's second law, momentum, or energy, and show how they can all be used to represent and explain changes in motion of a single object or multiple objects.
- Work on the skill of qualitative-quantitative translation. This includes three conceptual pieces: (1) Mathematically recognizing the functional dependence of one variable on another; (2) Recognizing how changing one physical quantity in an experiment affects other features of the experiment; (3) Showing how the mathematical dependence relates to the physical dependence

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

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Question #4 **Task:** Short Answer **Topic:** Waves - 3.A.1.1, 6.A.1.2, and 6.A.3.1

Max. Points: 7 **Mean Score:** 2.48

What were the responses to this question expected to demonstrate?

- An understanding of the instantaneous velocity and acceleration of points in a medium that carries a transverse wave.
- An understanding of the forward motion of a transverse wave along a rope during an interval of time.
- The ability to demonstrate knowledge that the motion of individual points on a rope carrying a transverse wave is perpendicular to the direction of the wave's propagation.

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?

- In Part (a), students were asked to draw arrows showing the instantaneous velocity and acceleration of two points on the rope as the wave passed by those points. They were not required to provide an explanation or justification.
  - Students generally performed better with the acceleration arrows than the velocity arrows.
  - Some students treated the picture as if it was a sinusoidal graph, rather than a picture of a rope carrying a transverse wave at an instant in time.
  - Many students earned points by drawing arrows in seemingly arbitrary directions that happened to match the rubric. Since no explanation or justification was required, this is where a lot of students picked up points despite little other evidence that they have an understanding of waves.
- In Part (b), students were given a picture of a wave and asked to draw the wave ¼ of a period later. There was a point P on the wave indicated on the diagram. They should have drawn the wave shifted by ¼ wavelength to the right.
  - Students often confused what was being asked in this question. Many drew a wave that had a period reduced to T/4. Some drew the wave with ¼ of the amplitude when compared to the original wave. Many drew the wave exactly as it was, but with the point P moved to the right along the contour of the wave by ¼ wavelength.
  - Some students interpreted the diagram as a standing wave and drew the wave ¼ of a period later as a flat line.
  - The question also asked the students to indicate where point P would be on their newly drawn wave. This question is asking them if they know that an individual point in the transverse wave just moves up and down perpendicular to the wave's propagation. Student performance was largely unsuccessful when completing this part; many students drew point P everywhere throughout the diagram.
- In Part (c), students were asked how far point P traveled in one period. This was asking them to calculate the distance that the point moves up and down in one complete wave cycle, which would be four times the amplitude.
  - Students often seemed confused by the question. When it asked how far point P traveled, many students thought it meant horizontally, rather than vertically. They also frequently gave an answer that indicated that the displacement is zero, despite the problem specifically saying "distance traveled (not the displacement)".

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Many students drew the same arrows for both velocity and acceleration, showing a confusion between those concepts.	• The correct response shows the velocity at zero when the point on the rope is at its greatest displacement from equilibrium (point P), and an upward arrow when the point on the rope is passing through equilibrium (point Q).
• Many students confused the velocity and acceleration of the points on the rope (up and down) with the direction of the traveling wave (to the right). These students drew arrows to the right at points P and Q.	• The correct response shows the velocity at zero when the point on the rope is at its greatest displacement from equilibrium (point P), and an upward arrow when the point on the rope is passing through equilibrium (point Q).
• Students often could not draw the wave in part (b). When asked to draw it after a time ¼ T had passed, they frequently drew the wave in the same place, but just shifted point P further to the right along the wave.	• The correct response shows that the wave should have been drawn with the same wavelength, shifted by one gridline (1/4 wavelength) to the right.
• When asked for the distance point P traveled in one period, the students often gave answers based on wavelength rather than amplitude, or calculated left-to-right motion of the point P when no such motion exists.	• The correct response in part (c) was 32 cm, calculated by knowing that point P on the rope will go only up and down, and not left-to-right. The point will move a distance equal to 4 times the amplitude in one wave period.

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?

To improve student performance:

- Teachers need to go into more detail about the motion of the medium in transverse waves. Students seemed generally confused on the exam about all details of the wave motion. There are excellent simulations available that show in slow motion the motion of particles in the medium in a transverse wave.
- It is important that students see waves in motion—through labs, videos, or simulations—and not just static images of waves drawn on a board. The motion of the medium is more clearly seen when it can be viewed in real time or slow motion with specific parts of the medium marked in some way.
- Teachers should distinguish between traveling waves and standing waves.

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 on the AP Central Home Page for AP Physics 1. The downloadable AP Physics 1 and AP Physics 2 lab manual may provide practical application of these concepts, and the downloadable reference guide for students, Quantitative Skills in the AP Sciences, may also prove to be helpful.

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Question #5

Task: Paragraph Length Response

Topic: Simple Harmonic Motion, Conservation of Momentum, and Conservation of Energy

Max. Points: 7

Mean Score: 0.94

What were the responses to this question expected to demonstrate?

- The ability to determine a numeric ratio of the periods of two oscillating systems of different mass.
- Recognition that mechanical energy is lost during an inelastic collision.
- Recognition that total mechanical energy in a system is conserved in the presence of conservative forces.
- The ability to write a logical, relevant, and coherent paragraph-length response to explain what happens to the amplitude of an oscillating system after a collision.

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?

- Many students were able to plug the given values into the equation for the period of a spring to solve for a ratio.
- Most students did not recognize that the inelastic collision resulted in the decrease of the velocity and kinetic energy of the system. Other than noting an increase in mass, the majority of students ignored the collision altogether.
- Many students described some form of energy conservation in their solutions. For those who correctly identified that mechanical energy was conserved during the post-collision oscillation, many overlooked the loss of energy during the collision and came to the wrong conclusion about the amplitude of oscillation.
- Some students understood that the system would contain spring potential energy when fully compressed, but did not equate maximum spring potential energy to the system's kinetic energy after the collision.
- The majority of responses had a paragraph that included supporting 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*
• Students indicated that mechanical energy is always conserved during a collision between objects.	• The correct response indicates that mechanical energy is lost during an inelastic collision.
• Students indicated that increasing the mass of an oscillating system does not change its amplitude because mass is not in the equation for the position of a simple harmoic oscillator, $x = Acos(2\pi ft)$.	• The correct response indicates that the addition of mass changes the angular velocity of the oscillating system, $\omega = 2\pi f$, which affects its position.
• Students indicated that the motion of a mass oscillating on a spring can be described with Newton's second law and/or Hooke's law.	• The correct response indicates that in the absence of non-conservative forces, the total mechanic energy of a system is conserved.

• Students indicated that increasing the mass of an oscillating system does not effect its amplitude because mass is not in the equation for spring potential energy, $U_s = \frac{1}{2}kx^2$. • Students indicated that the increase or decrease of one variable in the formula $K = \frac{1}{2}mv^2$ increases or decreases another due to the conservation of mechanical energy $(K_{max} = K_{max})$.	• The correct response indicates that the conservation of mechanical energy equates the initial energy of the system after the collision, $K_{max} = \frac{1}{2}mv^2$ and the final energy of the system, $U_{max} = \frac{1}{2}kx^2$.
• Students indicated that the total energy of the system increases when a larger value for mass is substituted into the equation for kinetic energy, $K = \frac{1}{2}mv^2$.	• The correct response indicates that the change in the mass of a system does not independently change the kinetic energy of the system. In the absence of external forces, momentum must be conserved, as well.

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:

- Avoid allowing students to simply reference an equation to justify a response. Most of the incorrect answers for this question were based off the result of plugging a larger mass into an equation or referencing an equation that doesn't have mass in it. Justifications should come from physics principle outlined in the learning objectives.
- Include sections which require the student to justify answers using words when creating assessments. Students can practice writing paragraph-length responses from released AP® Physics 1 exams and then review their responses using the published rubrics.

Students should:

- Practice analyzing situations with variables.
- Review a variety of collision types and learn the outcomes of each type.
- Recognize that there are many methods of solving problems that include forces and that the correct method is based on the type of force present. It may help if students are exposed to conservative/non-conservative and constant/varying forces on the same assessment.

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

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