Chief Reader Report on Student Responses:

2017 AP® Physics 2 Free-Response Questions

- Number of Students Scored 24,985
- Number of Readers 364
- Score Distribution

Exam Score	N	%At
5	3,223	12.9
4	4,162	16.7
3	8,484	34.0
2	6,889	27.6
1	2,227	8.9

- Global Mean 2.97

The following comments on the 2017 free-response questions for AP® Physics 2 were written by the Chief Reader, Peter Sheldon, Professor of Physics, Randolph College. 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.

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Question #1 **Topic:** Fluids

Max. Points: 10 **Mean Score:** 4.37

What were responses expected to demonstrate in their response to this question?

This question assessed learning objectives 3.A.2.1, 3.B.1.4, 5.B.10.1, 5.B.10.3, 5.B.10.4, and 5.F.1.1.
The responses to this question were expected to demonstrate the following:

- Understanding of the equation of continuity for fluids.
- The ability to reason about how fluid pressure depends on both speed and height, according to Bernoulli's equation.
- The understanding that kinetic energy increases if work is done on a system, and can do so even when the gravitational potential energy of the system also increases.
- The ability to calculate fluid pressure and fluid speed using correct principles and correct substitution.
- The understanding that pressure for a static fluid depends on depth and external atmospheric pressure.
- The understanding that the buoyant force is the net force exerted by the fluid and is directed upwards.
- The understanding that the buoyant force equals the weight of the displaced fluid.

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 revealed that students typically understand that pressure decreases when speed increases, but pressure's dependence on depth when the fluid was flowing was often ignored.
- Responses demonstrated student ability to apply the equation of continuity, both qualitatively and quantitatively.
- Responses did not adequately express the concept that pressure differences do external work.
- The majority of responses showed student realization that the equation of continuity and Bernoulli's equation both applied to this problem.
- The majority of responses demonstrated student understanding that pressure on a static fluid depends on depth.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Fluid pressure depends equally on both depth and speed.	• According to Bernoulli's equation, if the speed increases the pressure decreases, and if the height increases the pressure decreases. If both speed and height increase, as is the case here, the fluid pressure must decrease.
• If potential energy increases, kinetic energy must decrease.	• As the fluid flows up, gravitational potential energy increases. The kinetic energy also increases, since the speed increases. According to the equation of continuity, a smaller cross-sectional area (as is the case here) results in a larger speed.

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• The ‘y’ or ‘h’ in Bernoulli’s equation represented the same quantity as the ‘h’ or ‘d’ in the equation for pressure dependence on depth for a static fluid.	• To demonstrate understanding, the student will substitute the correct value into the appropriate equation, according to the diagram and the question.
• The buoyant force and the force from the fluid pressure are different forces.	• To demonstrate understanding, the student will draw one upward buoyant force, or several forces from the fluid pressure on all sides with the upward forces larger than the downward forces, but not both.
• Narrower tubes imply greater pressure since the cross-sectional area is smaller in the equation F/A and only that change will alter the fluid pressure.	• Since the tube narrowed, the speed increased based on the equation of continuity. A greater speed will cause the pressure to decrease according to Bernoulli’s equation.
• Some students confuse the names of principles or what the principles represent. For example, the equation of continutiy is based on the conservation of energy.	• State the correct basis and names for the principles.

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?

- Students should practice explaining concepts.
- Students should be able to explain the difference between static and dynamic fluids, and how the principles for each are related.

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 2 can find useful resources in the Course Audit webpage and AP Central Home Page for AP Physics 2. The following curriculum module will provide additional information on these concepts: 1. Multiple Representations of Knowledge: Mechanics and Energy. The downloadable AP 1 and AP 2 lab manual may provide practical application of these concepts.

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Question #2 **Topic:** Lab question, resistivity

Max. Points: 12 **Mean Score:** 6.57

What were responses expected to demonstrate in their response to this question?

This question assessed learning objectives 1.E.2.1, 4.E.4.3, 4.E.5.3, 5.B.9.5, and 5.C.3.4.
The responses to this question were expected to demonstrate the following:

- The skill of drawing a circuit diagram with voltmeter and ammeter reasonably wired in.
- The skill of labeling axes with appropriate scale and plotting points, drawing a best-fit line, and calculating the slope from points on the line.
- The skill of planning an experiment to measure resistivity.
- The understanding of the relationship between resistance, resistivity, length, and cross-sectional area for a conductor.
- The understanding of Ohm's law.
- The skill of being aware of factors that may affect an experiment and explaining whether they should be of concern or not.

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 responses correctly drew a circuit diagram with the meters wired in correctly.
- Quite a few responses did not distinguish between quantities that are measured directly versus quantities that need to be calculated from measured quantities, such as diameter and area.
- Most responses did not express the appropriate level of detail in the procedure. Some had "collect the materials" as one step; and others had "connect a wire to one end of the power supply" followed by a minute description of wire connections.
- The majority of responses revealed knowledge of the relationship between resistance and resistivity, as well as Ohm's law.
- The graphs drawn in the responses showed varying levels of student ability. Setting up axes with proper scales and labels, drawing a best-fit line, and calculating the slope were well-integrated skills for the most part. However, there were many instances of:
    - Drawing the best-fit line through the first and last data points
    - Drawing the best-fit line with too many data points on one side
    - Not specifying the origin as one of the points (if appropriate) in calculating the slope
    - Not stating when linear regression on a calculator was used
    - Averaging the ratio of the data points rather than calculating the slope
    - Using less than half the grid
    - Plotting current as a function potential difference but neglecting to take the reciprocal of the slope to determine resistance
- Few responses correctly answered the question about how the internal resistance of the power supply will affect the resistance of the rod. The main issue was responses did not show recognition that the given voltage was measured across the rod and not across the power supply.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Resistance and resistivity do not depend on temperature	• Resistance depends on temperature.
• Resistance and resistivity are the same as each other.	• Resistance is a property of a device and depends on its geometry; resistivity is a property of a material.
• Ammeters and voltmeters can be attached to a ciruit in any way.	• Diagrams are drawn with ammeters in series and voltmeters in parallel to the rod.
• Data points are used to find the slope of the best-fit line, especially the first and last data points (even if they were not on the best-fit line).	• Use points on the best-fit line to calculate the slope. The best-fit line should have about equal number of data points above it as below it and should follow the trend of the data.
• The symbol ρ only represents density.	• The symbol ρ represents resistivity in this context.
• Students do not use multiple trials effectively to reduce uncertainty. The resulting plot should reflect the use of these trials. For example, voltage was kept constant and the experiment was repeated for all the rods. However, in the analysis, students plotted voltage on one of the axes.	• Consistent use of multiple trials in the experiment and plotted in the graph. For example, repeat for all the rods. Use quantities about the rods (resistance, length, area, length/area) as the quantity on the x- or y-axis.
• In the equation that connects resistance and resistivity, some treated all the quatities the same, as in an algebraic expression. This led to proposing to graph length as a function of area, with a slope of resitance over resistivity, when length and cross-sectional area are independent quantities.	• Plot resistance as a function of length over area, where the slope is resistivity.

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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?

- Practice constructing graphs and drawing best-fit lines to analyze data.
- Students should practice writing brief and coherent procedures. Avoid: "follow safety guidelines," "gather equipment," "record data," "set the ammeter on the table."
- Practice applying knowledge to new situations.

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 2 can find useful resources in the Course Audit webpage and AP Central Home Page for AP Physics 2. The following curriculum modules will provide additional information on these concepts: 1. Graphical Analysis, 2. Multiple Representations of Knowledge: Mechanics and Energy. The downloadable AP 1 and AP 2 lab manual may provide practical application of these concepts.

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Question #3

Topic: ray optics, refraction

Max. Points: 12 **Mean Score:** 6.27

What were responses expected to demonstrate in their response to this question?

This question assessed learning objectives 6.E.3.1, 6.E.3.3, and 6.E.5.1.
The responses to this question were expected to demonstrate the following:

- Students were expected to understand how images are formed by a convex lens. This included how the image "flipped" both vertically and horizontally.
- The ability to utilize basic optics equations to determine the focal length and magnification from given image distance and object distance.
- Students were asked to construct a ray diagram to verify the given image distance and the image size.
- This Qualitative Quantitative Translation question required the students to show how their calculated focal length and image size were represented in the ray diagram they drew.
- Students were tested on their understanding of the refraction that occurred at multiple interfaces, both going into the lens and exiting the lens. They were asked to compare how the degree of refraction when the glass lens was in air compared to when it was submerged in water. This included an explanation of how the submersion of the lens affected the focal length and image characteristics.

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?

- For successful responses, the prompts allowed the students to show their mastery of the knowledge and skills. Any misunderstandings or lack of knowledge was very clear. It was difficult for students to stumble onto the right answer.
- Responses indicated that students who had the skill of drawing a ray diagram were able to clearly show that ability. The ray diagrams of successful students often went beyond just the two required rays and showed all three rays commonly taught.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
Lens image is flipped vertically	Lens image is flipped both vertically and horizontally
Light ray bends down at first interface from air to lens, and then bends back to horizontal at second interface of lens to air	Light ray bends down at both interfaces
Submerging a converging lens in water turns it into a diverging lens	Submerging a converging lens in water makes the rays bend less, but still converge

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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?

- In part d(i), many students showed the rays only bending once which is a common shorthand that teachers use when showing refraction by lenses, but it leads the student into thinking that the ray only does bend once, not at each interface.
- Students should carefully read the question. The test developers spend a lot of time attempting to clearly cue the student into what we are looking for. An example would be in question d(ii), where many students failed to get all of the points because they simply did not provide all of the requested information.
- Related to this, if an explanation is requested the question often cues the student into what information they should use in the explanation. Once again for part d(ii), the student was requested to explain their answers by relating it to what they saw in the ray diagram they drew in part d(i). Many students provided OK responses, but they did not answer the question by tying it back into the diagram and therefor were not awarded that point.

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 **Topic:** electrostatics (paragraph)

Max. Points: 10 **Mean Score:** 3.43

What were responses expected to demonstrate in their response to this question?

This question assessed learning objectives 2.C.4.2, 3.C.2.3, 5.B.2.1, 5.B.4.1, and 5.B.4.2.
The responses to this question were expected to demonstrate the following:

- Demonstrate the ability to correctly sum vectors in the form of multiple electrostatic forces.
- Understanding how the fields from individual charges contribute to an overall electric field (through calculation).
- Understanding how to properly combine vector quantities in two dimensions (for the electric field) and scalar quantities (for the potential difference).
- Understanding that forces are applied to objects (in this case, charged particles), while potentials and fields are evaluated at specific locations (with or without objects there).
- Understanding that electric potential energy cannot simply be stored in a single charge, or just in an electric field by itself, but instead that the energy is stored within a system, due to multiple charges, or due to a charge moved through a potential difference.
- Understanding that in order to change the internal energy of a system, work must be done by an external force, so external forces were used to place the charges in their current arrangement, giving the system that amount of electric potential energy.
- Understanding the difference between electric potential at a certain point within a system, and the electric potential *energy* of the system as a whole, and recognizing that rearranging the charges requires work.

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

- The majority of responses demonstrated an understanding of the direction associated with the net force as well as the net electric field.
- The responses frequently demonstrated student understanding that the electric potential is a scalar quantity and that the electric field is a vector quantity. The responses did not always show an understanding of how to sum these different types of values.
- The responses frequently failed to show the steps in the actual *calculations*, and instead just showed a general equation, and an answer (sometimes with a partial explanation written) (e.g., $E = k\frac{q}{r^2}$, the 2Q charges cancel so $E = k\frac{3Q}{d^2}$)
- Many responses treated electric potential and electric potential energy interchangeably, which is not correct.
- Responses generally demonstrated an understanding that work is related to energy in some way, but failed to adequately articulate exactly how they are related.
- responses frequently assessed "the system" as "at point *P*" and discussed how the electric field or potential at *P* was affected by the movement of the charges. This analysis was often used in an attempt to explain what happens to the overall potential energy, rather than demonstrating an understanding that the energy in the system is stored within the entire four-charge system and not simply at point *P*.
- The responses often discussed changes in direction, magnitude, etc. without mentioning exactly which physical quantity they are discussing

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Forces (and fields) are simply added (or subtracted) based on magnitude alone with no regard for direction (as scalar summations)	• Cancelling components from the +2*Q* charges, and then adding the remaining two magnitudes
• Adding electric field vectors (in 1D) based on sign (ex: (+1) + (-2) = (-1) rather than assessing magnitude and direction separately	• One E field has a value of -2, but recognizing that it is in the same direction as the field with a +1 value, so adding the magnitudes (ex: |+1| + |-2| = 3)
• Ignoring the signs on a scalar summation (and simply adding magnitudes (ex: (+1) + (+2) + (+2) + (-2) = 7)	• Including signs in the calculation (ex: (+1) + (+2) + (+2) + (-2) = +3)
• Electrical potential energy is stored in a field (by itself)	• Electrical potential energy is the energy stored due to moving a charged particle into the electric field
• Electrical potential energy is stored in a charged particle (by itself)	• Electrical potential energy is the energy stored between interacting charged particles
• Electrical potential is the same as Electrical potential energy	• Potential energy is stored by moving a charge through an electrical potential difference
• If an electric field changes at a certain point within a system, then the energy of the system changes (or similarly, if the potential at a point doesn't change, then the energy of the system must not change)	• While E (at a point P) will change, and V (at P) will stay constant, the specific field or potential at P does not define the entire system. The energy of the system is based on the individual charges and their locations in relation to each other, so changing the position of each Q can (and does) change the U of the system
• Mentioning that the potential energy between the two +2Q's cancel in the original orientation	• There is potential energy due to the original placement of the two +2Qs, which will increase with the new arrangement due to their closer proximity

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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?

- Students should understand the difference between scalar and vector quantities and practice adding each type of value.
- Students should practice showing all their steps when performing calculations.
- Students should clearly differentiate between positions in space and actual particles.
- Students should understand how to apply the work-energy theorem to electrostatic cases. The electric potential energy of a system of charged particles can be changed by moving these (or other) charged particles in the electric field created by the system of charges.
- Students should understand the difference between fields, forces, potential, energy and how to apply these concepts to individual particles as well as systems.

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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