AP® CollegeBoard

# Chief Reader Report on Student Responses:

## 2021 AP® Physics 2 Free-Response Questions

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|---|---|---|---|
| • Number of Students Scored | 18,736 | | |
| • Number of Readers | 461 (for all Physics exams) | | |
| • Score Distribution | Exam Score | N | %At |
| | 5 | 2,884 | 15.4 |
| | 4 | 3,351 | 17.9 |
| | 3 | 6,003 | 32.0 |
| | 2 | 5,065 | 27.0 |
| | 1 | 1,433 | 7.6 |
| • Global Mean | 3.06 | | |

The following comments on the 2021 free-response questions for AP® Physics 2 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:** Thermodynamics

**Max. Points:** 10 **Mean Score:** 4.81

***What were the responses to this question expected to demonstrate?***

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

- Analyze a P vs. V graph to compare relative values of temperature based on states' pressures and volumes
- Analyze a P vs. V graph to calculate work through -P*ΔV (or -Area)
- Calculate thermal energy transferred using ΔU=Q+W given ΔU and W
- Make claims about sign and magnitude of work when analyzing processes in a P vs. V graph
- Explain a process on a P vs. V graph according to microscopic properties of gas (frequency of collisions between particles and container, average kinetic energy or average speed of particles, volume or distance or time for particles to move in)
- Make predictions about energy flow based on macroscopic properties of gas (T)

***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?***

- Overall, responses showed a good familiarity with pressure, volume, work, and energy in the context of the PV diagram.
- Common confusions included mixing up the sign on work, mixing up thermal energy transfer (Q) and internal energy change (ΔU), and mixing up temperature and thermal energy transfer (Q).
- In most cases responses adequately showed calculations, claims, predictions, and analyses where warranted.

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

| *Common Misconceptions/Knowledge Gaps* | *Responses that Demonstrate Understanding* |
|---|---|
| • Calculation of work failed to use the negative of pressure multiplied by volume change or used pressure change instead of average pressure | • Calculation of work included equation, numerical substitutions, and correct units or correctly referred to area under curve. |
| • Making the erroneous assumption that Q=0 when comparing a process where there was an equal initial and final temperature | • Recognizing that ΔU=0 when comparing a process where there was an equal initial and final temperature (either by recognizing that temperature is a reflection of internal energy or by showing a calculation of U=3/2 * PV) |
| • Making the erroneous assumption that W=0 for a complete cycle on a pressure vs. volume graph | • Recognizing that the magnitude of the net work on a gas is the enclosed area for a complete cycle on a pressure vs. volume graph and recognizing that the sign of the net work would be the same as the sign of the work with the largest area (or more generally, that the sign of the work is dependent on the direction of the process) |

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| • Difficulty distinguishing microscopic versus macroscopic descriptors | • Recognizing that temperature is the macroscopic descriptor while average kinetic energy or average speed is the microscopic descriptor relating to internal energy of a gas<br>• Recognizing that pressure is the macroscopic descriptor while average force due to frequency of collisions and/or impulse is the microscopic descriptor relating interactions between gas particles and container walls |

***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?***

- Emphasize that there are at least two microscopic reasons for the macroscopic description of pressure:
    - More pressure could come from higher impulse from each collision due to higher speed when temperature is higher.
    - More pressure could come from a larger frequency of collisions when the time between collisions is reduced due to a smaller volume.
- Envision the sign of the work during a process by comparing the direction of an outside force and direction of movement of a piston.
- Emphasize the difference between a state and a process by showing that a state is a location on a PV diagram and that a process is the curve between two states on a PV diagram.

**Question #2** **Task:** Experimental Design **Topic:** Ideal gases and fluids

**Max. Points:** 12 **Mean Score:** 4.12

***What were the responses to this question expected to demonstrate?***

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

- Describe a procedure to investigate the relationship between the density and pressure of a sample of an ideal gas
- Derive equations for the density and pressure of the gas using measured quantities
- Analyze a density vs. pressure graph to determine whether the sample of gas is indeed ideal
- Compare the first experiment to a new experiment involving a balloon that is submerged underwater
- Derive an equation for the applied force necessary to hold the balloon stationary underwater

***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 that could produce a complete procedure were able to:
  - Clearly describe how the independent variable would be varied more than twice.
  - Measure values that are measurable versus ones that require calculation, like radius versus area.
  - Make use of the provided equipment to vary the pressure applied to the sample of gas.
- Given known quantities, students were able to produce equations using given and measured quantities:
  - Derive an equation using quantities that they had measured, connecting part (a)(i) and parts (a)(ii) and (a)(iii).
  - Include atmospheric pressure when asked to derive the absolute pressure of the gas.
- When asked to analyze a graph, students were able to apply physics principles to their analysis of the graph:
  - Clear mentioning of a physics principle (ideal gas law).
  - Relate the quantities in the law to the slope/shape of the provided graph.
- Using Newton's second law, responses that addressed the content well were able to incorporate quantities that included correct subscripts applicable to the required quantity:
  - Utilized the density of water to determine the buoyant force acting on the balloon.
  - Included both the weight of the rubber part of the balloon and the gas inside the balloon.

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

- Students did not clearly describe conducting more than two trials. Often students made no mention of repeating the described procedure or varying the number of objects placed on the piston.
- The provided meterstick was used to "measure" things that are not possible like area or volume. Students should have measured the radius or diameter and the piston height and then calculate the area and volume.
- When asked to use measured quantities in their derivation, students used quantities that they did not explicitly measure in their procedure.
- Subscripts were often missing or switched from step to step during derivations.
- When requested to use a physics principle, students did not mention the physics principle they were using, neither by name nor through the providing of an equation.

| *Common Misconceptions/Knowledge Gaps* | *Responses that Demonstrate Understanding* |
|---|---|
| • Unclear description of multiple trials | • "I will place one object on the piston and measure the piston height using the meterstick. I will then add objects one at a time to the piston, each time I will measure the piston height. I will do this for ten different total number of objects." |
| • Using measured quantites in their derived equation | • "I will measure the radius (r) and height (h) of the piston. Then I will calculate the Area=$\pi r^2$ and the Volume =$\pi h r^2$." |
| • Proper use of subscripts | • "$m_o$ is used to represent the mass of the provided objects and $m_p$ is used to represent the mass of the piston." |
| • Proper siting of Physics principles to analyze a provided graph | • "According to the ideal gas law pressure and volume are inversely proportional. Since density is inversely proportional to volume, density and pressure should be directly proportional. The given graph does not have a constant slope; therefore, it does not represent an ideal gas." |

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

- Students should practice writing out experimental procedures. Routine writing up of lab reports will help provide this practice. Special attention should be paid to clearly describing what quantities are measured and what tools are used to measure them. It should also be required for students to clearly address varying the independent variable many times.
- Students should have the opportunity to derive equations involving multiple versions of the same quantity, for example, different objects that have different masses represented by the letter m and different subscripts. If they only have the chance to calculate things using numerical values, then this is challenging.
- The difference between proportional, directly proportional, and inversely proportional relationships should be discussed often. When a new physics equation is presented, talk about which variables are directly proportional and which are inversely proportional.
- When students provide justifications or explanations, they must be prompted to always cite a physics principle or law to support their answers.

**Question #3** **Task:** QQT **Topic:** Induction/Magnetism

**Max. Points:** 12 **Mean Score:** 3.25

***What were the responses to this question expected to demonstrate?***

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

- The relationship between current, magnetic field, and force on a moving charged particle
- Electromagnetic induction due to a changing magnetic field
- Electric power/energy dissipated by a resistor
- Interpretation of linear graphs
- Functional dependence in mathematical relationships

***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 indicated a lack of understanding of what was meant by “functional dependence” of a function on a specified quantity. The vast majority of responses either addressed why the specified quantity should or should not appear in the equation at all (rather than whether its function in the expression made sense), and a non-negligible number of responses analyzed the role of variables other than the quantity specified.
- Many students did not state that magnetic flux was a relevant concept in answering this question, and even many of the responses that mentioned magnetic flux did not articulate that the change in magnetic flux is what induces an EMF or current. Without this recognition, it was difficult for the response to properly apply an understanding of power.
- A number of responses tried (incorrectly) to apply the formula for the force on a current-carrying wire in an external magnetic field to determine how to change the current in an electromagnet to alter the force it was exerting on a moving charged particle.
- On average, when asked to describe how a graph would change when the circumstances were altered, students were able to identify specific characteristics of the graph (e.g., slope, maximum values, values at specific points).
- Most students indicated that reversing a current would reverse the direction of the magnetic force it exerted on a charged particle, but many of these responses did not include a discussion of magnetic field as part of the reasoning.

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

| *Common Misconceptions/Knowledge Gaps* | *Responses that Demonstrate Understanding* |
|---|---|
| • General lack of recognition of what the quantities on the equation sheet represented | • The energy dissipated is equal to the time interval over which it was dissipated multiplied by the power during that time. |
| • Lack of understanding of what functional dependence means | • Because the cumulative energy is equal to the power multiplied by the time interval, and because the power is dependent upon the EMF squared, which contains the time interval in the denominator, it is correct that the cumulative energy should be inversely related to the time elapsed. |

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|---|---|
| • The strength of a magnetic field determines the magnitude of an induced EMF (rather than the rate of change of the magnetic flux associated with the field) | • Because the magnetic field strength changes twice as much in the same amount of time as the previous situation, and because the area enclosed by the loop did not change between the two situations, the change in magnetic flux is twice as much in this new situation. Therefore the induced EMF is twice as much. |
| • Changing the resistance and/or current in a loop changes the potential difference/EMF of that loop | • When the resistance of the bulb is increased, because the EMF remains the same, the current in the loop is decreased. |
| • Misapplication of F=IlxB to express the force on a single moving point charge | • The magnetic force on a moving point charge may be expressed as F=qvxB, so to double the force, the B field must be doubled. The B field is directly proportional to the current, so to double the force, the current in the wire must be doubled. |

**Question #4** | **Task:** Paragraph Response | **Topic:** Wave-particle duality and photon-electron collision

**Max. Points:** 10 | **Mean Score:** 4.06

***What were the responses to this question expected to demonstrate?***

Responses to this question were expected to demonstrate that changes that occur as a result of interactions are constrained by conservation laws. They were also expected to demonstrate that photons can exhibit particle properties and that material particles can exhibit wave properties. Responses to this question were also expected to demonstrate that mass is part of the energy of a system. They were also expected to make predictions about the internal energy of a system and how that might change. They were also expected to use conservation laws to make predictions about how a system might change and how those changes would manifest in the system.

***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 to this question:

- Calculated the speed of a free electron given a specified wavelength.
- Calculated the energy of photons emitted in the collision and annihilation of an electron and a positron.
- Described with words, diagrams, and mathematics the outcome of a photon scattering off a free electron.
- Applied the principles of conservation of momentum and conservation of energy to the interactions of subatomic particles.

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

| *Common Misconceptions/Knowledge Gaps* | *Responses that Demonstrate Understanding* |
|---|---|
| • Units need to be considered when choosing a numeric value for a needed constant | • Responses that used the value of Planck's constant with units of J · s instead of eV · s |
| • Photons can lose velocity in a collision | • Responses that recognized that photons can lose energy in a collision but always move at the speed of light |
| • In two-dimensional elastic collisions, both objects must recoil on paths that are diametrically opposed | • Responses that recognized that in 2-dimensional elastic collisions the paths are determined by momentum conservation in both dimensions |
| • The frequency of a photon depends on its speed | • While the wavelength (and therefore frequency) of a photon depends on its momentum, that momentum cannot be thought of as mass times velocity |

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| • Velocity is conserved in a collision | • In a collision it is momentum that is conserved, not velocity |
| • Momentum is always proportional to velocity | • Responses that recognized that in particles exhibiting wave properties momentum is related to wavelength |

***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?***

Teachers should emphasize and model with their students that the choice of a numeric value for a needed constant is dependent on the units of that value, especially on the quantum scale where energy can be in units of joules or electron-volts.

Teachers should emphasize that on the quantum scale, mass-energy is just as important as kinetic and potential energies when conservation of energy is being used in the analysis of an interaction of a system.

Teachers should emphasize that while photons have properties such as momentum, those properties cannot be thought of as being exactly the same as when dealing with objects that have mass.