Chief Reader Report on Student Responses:

2024 AP® Physics 2: Algebra-Based Free-Response Questions

• Number of Students Scored	22,804		
• Number of Readers	685 (for all Physics exams)		
• Score Distribution	Exam Score	N	%At
	5	4,359	19.1
	4	4,105	18.0
	3	7,613	33.4
	2	5,214	22.9
	1	1,513	6.6
• Global Mean	3.20		

The following comments on the 2024 free-response questions for AP® Physics 2 were written by the Chief Reader, Brian Utter, teaching professor and associate dean of general education at the 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: Paragraph-Length Response
Topic: Properties of Waves and Particles, Photoelectric Effect
Max Score: 10
Mean Score: 3.60

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Relate the frequency of a photon to the energy of the photon.
- Relate the kinetic energy or speed of an electron to the de Broglie wavelength of the electron.
- Relate the energy of an incident photon to the energy of an electron ejected from a metal sample.
- Analyze the photoelectric effect to compare the kinetic energy of ejected electrons when the energy of incident photons exceeds the work function.
- Analyze the photoelectric effect to determine if electrons will be ejected when the energy of incident photons does not exceed the work function.
- Calculate the kinetic energy of electrons from a given de Broglie wavelength by analyzing the relationship between λ_e and p or v *and* the relationship between K and p or v.
- Analyze $K_{\text{max}} = hf - \phi$ to relate the energy of the incident photons and the kinetic energy of ejected electrons to the work function of different materials.

How well did the responses address the course content related to this question? How well did the responses integrate the skill(s) required on this question?

- By looking at the table of data, most responses correctly indicated the lowest frequency *or* the highest frequency of incident photons, while many responses correctly indicated both.
- When responses correctly claimed f_{B} was the smallest frequency, most correctly indicated that the frequency (or energy) of the photon was too low to eject an electron. Of those responses, only a small portion explicitly indicated that the reason was that the frequency or energy were below the threshold frequency or work function of the metal.
- Many responses incorrectly related the frequency of a photon to the wavelength of an ejected electron through the wave speed equation $v = f\lambda$. This resulted in a significant number of responses that ranked f_{C} as the largest frequency simply due to the smallest resulting λ_e without adequately relating the energy of the incident photon to the energy of the ejected electron. A small number of responses *did* correctly relate the greater electron energy to a greater photon energy as an indication that f_{C} was the largest frequency.
- Many responses referenced frequency and wavelength extensively but never connected either value to the energy of a photon or the energy of an electron.
- Some responses related the frequency of a photon to the energy of the photon explicitly through the equation $E = hf$, or implicitly while discussing light and/or photons. A significant number of responses mentioned wavelengths, frequencies, and energies of photons and electrons in a manner that was unclear that the *photon* frequency was being related to the *photon* energy. Many responses mentioned frequency and energy in a manner that was unclear if it was in reference to the photons or electrons.
- Many responses attempted to determine electron energy by incorrectly using the wave equation $v = f\lambda$ with $E = hf$ or with $E = \frac{hc}{\lambda}$.
- Most of the responses that used $\lambda_e = \frac{h}{p} = \frac{h}{mv}$ to relate the de Broglie wavelength to the electron speed and/or energy did so correctly.

- When using Planck's constant h and/or electron mass m_e, most responses used the correct values. However, many responses incorrectly used the speed of light, c, as the speed of the electron, resulting in incorrect energy values.
- Most responses correctly identified the equation $K_{\max} = hf - \phi$ as it applies to the photoelectric effect, and many responses correctly made claims that when photons of the same frequency were incident, an ejected electron with greater kinetic energy was due to a smaller work function. However, very few responses correctly justified how it was determined that K was greater and/or that the energy of the photons was the same.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Using the de Broglie wavelength of a particle in a wave equation that applies to a photon (such as $v = f\lambda$ or $E = \frac{hc}{\lambda}$) to incorrectly compare frequency or energy of a photon to wavelength of an electron. e.g., Wavelength and frequency are inversely related according to $v = f\lambda$, so the lower de Broglie wavelength corresponds to a higher photon frequency.	Using an appropriate relationship between the de Broglie wavelength of a particle and its momentum to determine p, v, and ultimately the energy of an electron, to then compare to the energy of a photon. • e.g., The de Broglie wavelength of an ejected electron is inversely related to the momentum, speed, and, therefore, energy of the electron. So, a larger photon energy results in greater kinetic electron energy for an ejected electron.
• The wavelengths listed on the table are the wavelengths of the incident photons.	• The wavelengths listed on the table are the de Broglie wavelengths of the ejected electrons.
• The energy of the ejected electron is equal to the energy of the incident photon.	• The energy of the ejected electron is equal to the energy of the incident photon minus the work function, according to $K_{\max} = hf - \phi$.
• Correlating the given de Broglie wavelength to the quantity of ejected electrons.	• The de Broglie wavelength is a measurement associated with each electron, not an overall quantity of electrons.
• Using the relationship between energy and wavelength or frequency of a photon ($E = hf = \frac{hc}{\lambda}$) to determine the energy of an electron.	• Using an appropriate equation relating energy of an electron to mass, velocity, and/or momentum of a particle ($K = \frac{1}{2}mv^2$ or $K = \frac{p^2}{2m}$).
• Using the speed of light, c, for the speed of an electron.	• Only use the speed of light, c, when analyzing light. The speed of the electron can be found using $\lambda_e = \frac{h}{mv}$.

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

- Encourage students to use precise language when describing multiple items. Many responses used phrases like “it has more energy” or “they have a greater wavelength,” which led to ambiguity of the subject. Using precise language such as “the photon has more energy” or “the ejected electrons have a greater wavelength” will improve the clarity of the response.
- Emphasize the importance of providing an appropriate link using physics relationships between different quantities. Using appropriate equations can provide useful links, such as $E = hf$ to link photon frequency to energy, or $\lambda_e = \frac{h}{p} = \frac{h}{mv}$ to link the de Broglie wavelength of an electron to the speed of an electron.
    - For example, relating energy of a photon and energy of an ejected electron is a comparison between two energy values. However, relating frequency of a photon and energy of an ejected electron requires a link between frequency of a photon and energy of a photon first.
    - For example, relating photon frequency to threshold frequency is a comparison between two frequency values. However, relating photon frequency to work function requires a link between photon frequency and photon energy, which can then be used to compare photon energy to work function.
- Emphasize the difference between equations that relate properties of a wave and equations that relate properties of a particle, with a focus on using only the relationships that apply to a given situation.
- Emphasize the importance of referencing all expressions within an equation to justify a conclusion.
    - For example, when analyzing $K_{\text{max}} = hf - \phi$ to compare work functions, it is necessary to provide information about both K_{max} and hf to determine ϕ.

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 the AP Daily videos on the photoelectric effect and de Broglie wavelength.
- Teachers should assign topic questions as well as personal progress check items to monitor progress being made in the mastery of content.

Question 2

Task: Experimental Design
Topic: Thermodynamics, Ideal Gas Law, Thermal Conductivity
Max Score: 12
Mean Score: 7.10

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Describe a procedure to properly collect data that can be used to determine the number of molecules of a gas in a chamber using the ideal gas law.
- Sketch a thermodynamic process on a PV diagram: draw a line and an arrow on the line to show the relationship between the pressure and volume of a gas in a chamber of fixed volume as the temperature of the gas increases.
- Sketch a thermodynamic process on an internal energy versus volume diagram: draw a line and an arrow on the line to show the relationship between the internal energy and volume of a gas in a chamber of fixed volume as the temperature of the gas increases.
- Justify the shape of the sketch of the relationship between the internal energy and volume of a gas in a container of fixed volume as the temperature of the gas increases.
- Recognize how the equation for the rate of energy transferred by conduction can be used to determine the thermal conductivity of a material by selecting appropriate variables to graph.
- Plot data with appropriate scaling and label axes of a graph with the appropriate quantities and units.
- Draw a best-fit line that follows the trend of the data.
- Use the slope of the best-fit line and appropriate equation to determine the thermal conductivity of a material.

How well did the responses address the course content related to this question? How well did the responses integrate the skill(s) required on this question?

- Most responses showed an understanding that it was necessary to measure the pressure and temperature of the gas in the chamber using the provided sensors. However, many responses were unclear about whether the measurements should be taken at multiple different temperatures because they only indicated that the experiment should be completed several times without explicitly stating that the temperature should be changed several times.
- Many responses showed an understanding that just because the chamber was rigid, it didn't mean that the volume was known and that it was necessary to measure the dimensions to calculate the volume.
- Many responses correctly drew a straight vertical line for the PV diagram and internal energy versus volume diagram, but many also incorrectly started the line on the horizontal axis, which would indicate zero pressure or zero internal energy.
- Most responses correctly justified the shape of the internal energy versus volume diagram by describing both the fact that the process was isovolumetric and that there was an increase in internal energy as energy was added to the gas by the heater.
- Many responses plotted data and drew a best-fit line, but the graph was often plotted with incorrectly selected variables (axes) that did not give the experimental value for thermal conductivity.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Thinking that because the chamber was rigid meant that the volume was known.	• Taking measurements of the dimensions of the chamber to calculate the volume of the gas.
• Only indicating that one measurement should be taken or indicating that the experiment should be completed multiple times without explicitly stating that the temperature should be changed to many different values.	• Stating that the gas should be heated to many different temperatures and the pressure should be recorded at those temperatures.
• Not recognizing that starting a sketch of pressure versus volume or internal energy versus volume on the horizontal axis indicates zero pressure or internal energy.	• Sketching a PV diagram and an internal energy versus volume diagram that start above the horizontal axis.
• Confusing the quantity ΔT in the thermal conductivity equation for the change/increase in temperature of the liquid as it was heated instead of the temperature difference between the liquid and the gas.	• Calculating the difference in temperature between the gas and liquid for each trial.
• Incorrectly manipulating the appropriate equation such that the experimental value of thermal conductivity could not be determined from the graph.	• Plotting quantities such that the slope could be used to determine the experimental value for the thermal conductivity of the material. For example by graphing $\frac{Q}{\Delta t}$ versus ΔT or $\frac{Q}{\Delta t}$ versus $\frac{A\Delta T}{L}$.
• Not labeling axes with both the quantity and the units or not having the units match the graphed quantities.	• Properly labeling both axes with the appropriate quantities and matching units.
• Only using a small portion of the provided graph space to plot the data.	• Choosing a scale that results in data points spread over more than half the area provided to plot the data.
• Drawing a best-fit line by hand that does not accurately follow the trend of the data.	• Use of a straight edge/ruler to draw one distinct best-fit line that follows the trend of the data.

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

- Students need to practice not just plotting data on graphs but also sketching qualitative graphs that show how quantities change with respect to one another.
- While teaching the concepts of thermal conductivity and rate of energy transferred by heating it should be emphasized that ΔT represents a difference in temperature from one side of a material to the other side of the material and not a change in temperature of either side of the material through which energy is being transferred by conduction.
- Have students manipulate equations to determine quantities that can be graphed to yield a straight line and determine how that graph will provide the requested information.
- Most students did not fill out the extra column for their calculated values which would have helped them more accurately determine the scale to use on the graph as well as improve their plotting of data.
- Students need to graph data by hand often. It was clear that this is a skill that, while it is improving, is still a struggle for many students.
    - Data from hands-on experiments should be graphed. Data sets can also be generated to graph quickly from online simulation sites to help students focus on graphing skills without the distraction of data that may not produce a straight line.

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 the AP Daily videos on thermodynamics, the ideal gas law, and thermal conductivity.
- Teachers should assign topic questions as well as personal progress check items to monitor progress being made in the mastery of content.

Question 3

Task: Qualitative-Quantitative Translation
Topic: Electric Circuits
Max Score: 12
Mean Score: 5.50

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Determine the equivalent resistance of a circuit containing resistors in both series and parallel.
- Derive mathematical expressions for the current in a resistor in series with the battery and the current in a resistor on a parallel branch of a circuit using Ohm's law and Kirchhoff's laws.
- Demonstrate understanding of the relationships among potential differences across each resistor in a circuit through the use of a bar chart.
- Analyze a given expression for power to determine if it is correct based on previous circuit analysis.
- Apply functional dependence to determine how the addition of a nonideal battery to a circuit affects the rate at which energy is dissipated across a resistor in the circuit.

How well did the responses address the course content related to this question? How well did the responses integrate the skill(s) required on this question?

- Most responses recognized the need to determine the equivalent resistance of the circuit as part of deriving the current in a resistor in series with a battery. However, a significant number of responses were unable to correctly determine the equivalent resistance of the circuit due to incorrect application of the equivalent resistance expressions and due to algebraic mistakes.
- The responses mostly showed recognition of the need to apply Kirchhoff's junction rule to determine the current in a branch of the circuit, though most did not correctly determine the ratio of the currents entering and exiting the junction.
- Most responses correctly identified that the potential differences across identical resistors in series are the same and that the potential differences across two parallel branches are the same.
- Most responses did not correctly determine the relative values of the potential differences across each of the resistors.
- Most responses were able to correctly recognize whether the given expression for power was correct, consistent with work in previous sections.
- Most responses recognized the need to utilize an expression for power to justify their statement, but many did not correctly proceed to substitute values from previous sections.
- The vast majority of responses recognized that the addition of a nonideal battery would reduce the power dissipated across a resistor in series with a battery.
- Most responses correctly justified how the addition of a nonideal battery to the circuit would reduce the power dissipated by *the entire circuit* but did not go on to explain why the power dissipated by the *specified resistor* would be reduced. Responses should always endeavor to answer the question that was asked.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Providing an incorrect algebraic solution for equivalent resistance with resistors in series and parallel	• Showing that resistors in series add and resistors in parallel add as inverses, so for this problem, $R_{\text{total}} = R + \dfrac{1}{\dfrac{1}{R} + \dfrac{1}{R+R}} = \dfrac{5R}{3}$.
• Solving for various currents in the circuit without realizing the current needed is that in the battery	• The current in any resistor in series with an emf source will be the same as the current in that emf source. $I_1 = I_{\text{battery}} = I_{\text{total}}$
• Not applying Kirkhoff's laws	• Correct responses show proper applications of the junction rule combined with a loop rule expression as shown in the example solution in the scoring guidelines for part (a)(ii).
• Not recognizing that the sum or potential differences in any closed loop equals zero	• When looking at the potential differences shown in the bar chart, responses should show: ○ $\Delta V_1 + \Delta V_2 = \mathcal{E}$, ○ $\Delta V_1 + \Delta V_3 + \Delta V_4 = \mathcal{E}$, ○ $\Delta V_2 + \Delta V_3 + \Delta V_4 = 0$.

• When using $P = \frac{V^2}{R}$ or $P = I^2 R$, responses would often use just the value R instead of substituting in R_{total}.	• When analyzing power dissipated by an entire circuit the analysis must include: ○ emf provided by the battery ○ battery current **and/or** ○ total resistance of the circuit. i.e., $P = I\Delta V \rightarrow P = I_1\mathcal{E} \rightarrow P = \frac{3\mathcal{E}}{5R}\mathcal{E} = \frac{3\mathcal{E}^2}{5R}$ OR $P = \frac{V^2}{R} \rightarrow P = \frac{\mathcal{E}^2}{R_{\text{total}}} = \frac{3\mathcal{E}^2}{5R}$ OR $P = I^2 R \rightarrow P = I_1^2 R_{\text{total}} \rightarrow P = \left(\frac{3\mathcal{E}}{5R}\right)^2\left(\frac{5R}{3}\right) = \frac{3\mathcal{E}^2}{5R}$

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

- Students should practice finding the equivalent resistance of circuits where the value of the resistors is in terms of R rather than numeric values.
- Students should practice writing junction rule and loop rule equations for circuits containing various combinations of resistors and then use those equations to determine the relative currents in and potential differences across those resistors.

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 the AP Daily videos on electric circuits, Kirchhoff's laws, and adding resistors in parallel and series.
- Teachers should assign topic questions as well as personal progress check items to monitor progress being made in the mastery of content.

Question 4

Task: Short Answer
Topic: Electric Charges and Fields, Conservation of Electric Energy, Magnetic Fields and Forces
Max Score: 10
Mean Score: 3.58

What were the responses to this question expected to demonstrate?

The responses were expected to demonstrate the ability to:

- Relate the kinetic energies of two charged particles that are accelerated from rest through an electric potential difference as a ratio.
- Determine an expression for the speed of a particle using its kinetic energy.
- Derive an expression for the speed of a charged particle in the presence of a magnetic field using Newton's second law of motion.
- Sketch the path of a charged particle moving through a uniform magnetic field.
- Determine the direction of an electric field that would allow a charged particle to move through a magnetic field with a constant velocity.

How well did the responses address the course content related to this question? How well did the responses integrate the skill(s) required on this question?

- Overall, responses tried to calculate a ratio of kinetic energies using an appropriate conservation of energy equation. However, many responses attempted to calculate the ratio by simply manipulating the equation for kinetic energy, rather than relating the final kinetic energy to the change in potential energy.
- Most responses correctly determined the speed of Particle 2 by manipulating the appropriate equation for kinetic energy. The most common error was simply that the students did not substitute the correct mass for Particle 2 into the rearranged equation.
- Most responses indicated an understanding that the magnetic force on the charged particle was the net force and then properly applied Newton's second law.
  - However, many responses did not identify that the net force would cause circular motion and did not indicate the acceleration would be centripetal. Student responses often attempted to apply linear kinematics equations.
  - Most of the responses did show an attempt at performing the necessary substitutions for the mass, charge, and speed of Particle 2. Often these substitutions were unclear, and it was difficult to identify what was being substituted and for what quantity. Also, frequently one or more of the substitutions were not performed.
  - Most of the responses that recognized this was centripetal motion correctly identified the distance asked for was $\Delta x = 2r$ and attempted to apply this in their derivation.
- Many of the responses showed a clear attempt at applying the right-hand rule to determine the paths of the particles. The paths of the particles were curved and often, the curves were in opposite directions, showing that the responses indicated an understanding of the relationship between different charge signs and the magnetic field. However, the correct connection between the magnetic field and the size of the path was not as commonly shown.
- Responses showed a strong understanding of how to determine the direction of the electric field. A sizable number of responses did confuse electric force with electric field or did not properly apply the right-hand rule for the negative charge of Particle 1 which led to an error when determining the correct direction for the electric field.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
• Not recognizing that kinetic energy can only change when work is done. In this instance, the work is done by the electric field that the two charged particles are accelerated through.	$K_1 = Q\lvert\Delta V\rvert$ or $q\Delta V = \frac{1}{2}mv^2$ • These responses correctly identify the relationship between the work done by the electric field and the change in kinetic energy for a charged particle accelerating from rest through a potential difference.
• The kinetic energy of a particle does not need to be calculated directly from the kinetic energy equation but should be calculated using the equation for the quantity that is causing the change in kinetic energy.	$K_2 = q\Delta V = 2Q\lvert\Delta V\rvert$ • Determining the kinetic energy using the equation for work done by an electric field on a charged particle, which is then equal to the kinetic energy acquired by that charged particle.
• Not substituting the appropriate quantities into the equations.	• Properly substituting previously computed quantities: $v = \sqrt{\frac{2K_2}{M}} = \sqrt{\frac{2K_2}{M / 2}} = \sqrt{\frac{4K_2}{M}}$ $\Delta x = 2\left[\frac{\left(\frac{M}{2}\right)\sqrt{\frac{4K_2}{M}}}{2QB_0}\right]$
• When deriving an expression, the responses did not start with fundamental principles. • Some responses just had the equation $r = \frac{mv}{qB}$ without any supporting steps.	$F = ma$, $F_M = ma$, or $qvB = ma$ • The responses need to start with fundamental principles and clearly show the correct substitutions in an organized manner.

• Using a linear kinematic expression for the acceleration of the charged particle rather than the equation for centripetal acceleration.	$$qvB = ma = \frac{mv^2}{r}$$ • Understanding that because the charged particles are moving through a magnetic field, the resulting path will be circular.
• Understanding the difference between forces and fields. Responses sometimes determined the correct direction for the electric force but did not then determine the correct direction for the electric field.	• The magnetic force will make the negatively charged Particle 1 curve to the right following the right-hand rule. For Particle 1 to move in a straight line at a constant speed, an electric force to the left must be exerted on the particle. Because the particle is negatively charged, the electric field must be directed in the opposite direction of the force and therefore, the electric field must be directed to the right. • This question used the "determine" task verb, therefore a correct response just needed to state to the right.

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

- Reinforce that conservation of energy principles learned in AP Physics 1 still apply in AP Physics 2 and how to correctly apply them in various situations. For example, in relating the work done on a charged particle to its kinetic energy, or the idea that $\Delta U + \Delta K = 0$.
- Practice derivations beginning from fundamental principles and clearly substituting given variables. A good strategy is to start with an applicable equation from the equation sheet and substitute symbolic quantities and variables based on the specific problem to solve for the desired quantity. This is a good practice to reinforce even with problems that involve numerical solutions.
- Demonstrate the proper application of the right-hand rule for charged particles moving through magnetic fields.
- Demonstrate and explain the relationship and differences between electric charge, electric force, and electric fields.

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 the AP Daily videos on electric charges and fields, conservation of electric energy, and magnetic fields and forces.
- Teachers should assign topic questions as well as personal progress check items to monitor progress being made in the mastery of content.