



Student Performance Q&A: 2014 AP[®] Chemistry Free-Response Questions

The following comments on the 2014 free-response questions for AP[®] Chemistry were written by the Chief Reader, Roger Kugel of the University of Cincinnati in Cincinnati, Ohio. 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 performance 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

What was the intent of this question?

Question 1 assessed students' understanding of the principles and practice of gravimetric analysis. Students were presented with data from an experiment precipitating $I^{-}(aq)$ from a solution prepared by dissolving a tablet containing KI and an inert, water-soluble sugar and adding excess $Pb(NO_3)_2(aq)$. In part (a) students had to write the net-ionic equation for the reaction that occurs, and to explain why the net-ionic equation is the best representation of the reaction. Parts (b) and (c) assessed the students' understanding of the design and implementation of the experiment – students were asked to explain the reason for repeated drying and weighing of the precipitate and to demonstrate an understanding of the composition of the filtrate. In parts (d) and (e), the students were required to use the given data to determine, ultimately, the mass percent of I^{-} in the tablet. Part (f) again assessed experimental design, and asked the students to predict how a change in the experimental procedure (dissolving the tablet in 55.0 mL of solution rather than 50.0 mL) would affect the results and to justify their prediction. Finally, in part (g), a similar experiment was described using $0.20\ M\ AgNO_3(aq)$ rather than $0.20\ M\ Pb(NO_3)_2(aq)$. In part (g)(i), students were given the value of the K_{sp} of AgI and asked to predict if the addition of $0.20\ M\ AgNO_3(aq)$ would precipitate I^{-} from the solution. Part (g)(ii) asked how the precision of the experimental mass of AgI precipitate would be affected if the experimenter had access only to one tablet and to a balance that can measure to the nearest 0.01 g.

How well did students perform on this question?

This question did an excellent job discriminating between students in terms of their understanding of the principles and practice of gravimetric analysis, presumably reflecting course time spent doing meaningful laboratory work. The mean score was 3.41 out of a possible 10 points.

What were common student errors or omissions?

Part (a)(i): Students generally did well on part (a)(i), and students who did not earn credit on this accessible question usually did poorly on the remaining parts. Common errors included:

- Incorrect charges on ions leading to an incorrect precipitate formula
- Failure to balance the equation

Part (a)(ii): Students who earned credit for correctly responding to part (a)(i) almost universally earned credit for this part as well. Students who did not earn credit here often gave a general definition of a net-ionic equation rather than an explanation of why the net-ionic equation is the best representation for this particular experiment. Students who did not write a correct net-ionic equation often did not earn credit on this part. The most common errors were:

- Writing general statements rather than addressing the equation
- Writing explanations that were inconsistent with their response in part (a)(i)

Part (b): This part seemed to discriminate between the students who understood the reason for data collection (likely because they've done a similar laboratory exercise) and the students who may have only solved textbook problems related to gravimetric analysis. Common poor responses included vague statements such as:

- "To make sure that the precipitate is pure."
- "To get a more accurate mass of precipitate and filter paper."

A surprising number of students wanted to take an average of the three weighings to find the most accurate measure of the mass of the dried sample.

Part (c): To earn the point in part (c), students had to realize that $[K^+] < [NO_3^-]$ because the $Pb(NO_3)_2(aq)$ solution was added in excess.

There were two common student errors in this part.

- Comparing the $[K^+]$ and $[NO_3^-]$ in the stock solutions ($[K^+]$ often calculated by presuming that the tablet was pure KI, and $[NO_3^-]$ taken as either 0.20 M or 0.40 M from the given $[Pb(NO_3)_2]$)
- Using the stoichiometric relationship in the overall equation to compare moles of K^+ and NO_3^- in the reaction

Part (d): Students had to subtract the mass of dry filter paper from the correct dried mass of precipitate plus filter paper. Then they had to divide the resulting net mass by the molar mass of PbI_2 . Commonly, students failed to subtract the mass of dry filter paper, or they computed the molar mass of PbI_2 incorrectly, or they made a general calculation error. These students failed to earn the point in part (d). However, students who thought the precipitate was PbI and failed to earn the equation point in part (a), could still earn the point in part (d) for correctly computing the moles of PbI precipitate consistent with their equation in part (a).

Part (e): To find the percent I^- in a tablet, students had to first determine the mass of I^- in the experimental tablet, and then divide it by the mass of tablet to get a percent. An answer consistent with an incorrect number of moles of PbI_2 in part (d) could receive full credit in part (e). Common errors were made by students who failed to use the experimental data properly or at all. Instead, they calculated the percent I^- in pure KI (76.4 percent) or in pure PbI_2 (55.1 percent). These answers received no credit in part (e).

Part (f): Most responses correctly stated that the modification in experimental procedure (dissolving the tablet in 55.0 mL of water rather than 50.0 mL of water) would have no effect on the mass percent of I^- in the tablet. However, many of these responses did not earn credit because the justification was insufficient.

- The justification often restated the assertion, "...because the amount of water does not affect the mass percent I^- ."
- The response referred to the mass percent of I^- in the tablet, rather than the experimental value obtained from the data (this often followed from an incorrect theoretical mass percent of I^- in pure KI in part (e)), "...the amount of solvent doesn't change the mass percent I^- in the tablet."

Part (g)(i): Students did not refer to the mass of the AgI precipitate (likely because they did not calculate its value).

- Many good papers missed this point because they referred to the mass of the tablet rather than the AgI precipitate, "The mass of the tablet can only be measured to two significant figures."
- Students erroneously assumed that the mass of AgI precipitate was based on the mass of the tablet, "Because the mass of the tablet can only be measured to two significant figures, the mass of the precipitate, AgI, can only be expressed to two significant figures."
- Students did not discriminate between decimal places and significant figures, "The balance can only measure to two significant figures." or, "The balance can only measure to one significant figure."

Based on your experience of student responses at the AP[®] Reading, what message would you like to send to teachers that might help them to improve the performance of their students on the exam?

Students need to perform meaningful (non-rote) laboratory work and to understand the reasoning behind each step in the procedure. Responses on this question seemed to discriminate quite well between students who have an understanding of gravimetric analysis and those who are unfamiliar with this common laboratory procedure. While it is unnecessary to perform this particular experiment (determination of I^- using Pb^{2+}), common laboratory practices should be done by the students. This is an ideal experiment for error analysis and student-generated procedures (i.e., "inquiry").

Question 2

What was the intent of this question?

This question was designed to assess students' conceptual and analytical understanding of acid-base chemistry. Part (a) asked students to identify a Brønsted-Lowry conjugate acid-base pair from an equation provided. Part (b) asked students to calculate the K_a for propanoic acid given a pH and concentration. In part (c) students were provided with two statements and asked to identify each as true or false and support their answers with reasoning. In part (c)(i) the question assessed conceptual understanding of pH when equal volumes of equimolar strong base and weak acid solutions were mixed. In part (c)(ii) the question assessed conceptual understanding between concentration and pH of strong acid and weak acid solutions. Part (d) required students to calculate the molar concentration of propanoic acid given titration data. Part (e) assessed analytical and conceptual understanding of $\text{p}K_a$ values and indicators.

How well did students perform on this question?

Overall, students performed reasonably well when answering this question. The mean score was 3.99 out of 10 possible points.

In part (b) many students were able to calculate the K_a value for propanoic acid from the solution pH and earn all three points. In part (c)(ii) most students earned one point for identifying the difference in

dissociation between a strong acid and a weak acid to support the true statement. In part (d) many students received two points for calculating the initial molarity of the propanoic acid in the titration described. Most students invoked the $M_a V_a = M_b V_b$ equation. Part (e) proved a bit more challenging for students both qualitatively and quantitatively. Many students realized that the K_a and pK_a of a weak acid affected the claim of indicator choice but had difficulty explaining this.

What were common student errors or omissions?

Part (a): Students demonstrated their qualitative misunderstanding of Brønsted-Lowry conjugate acid-base pairs by:

- Identifying each component in the reaction but not identifying a specific pair
- Identifying either both reactants or both products as the conjugate acid-base pair
- Pairing of acid/conjugate acid and base/conjugate base
- Omitting charges on propanoate ion or hydronium ion
- Writing the formulas for propanoic acid and/or propanoate ion incorrectly

Part (b): Students showed their quantitative misunderstanding of general acid-base chemistry in various ways as well. These included:

- Assuming that $\text{pH} = \text{p}K_a$ and solving for K_a using this expression
- Incorrectly applying the Henderson-Hasselbalch equation
- Failing to recognize that $[\text{H}_3\text{O}^+] = [\text{CH}_3\text{CH}_2\text{COO}^-]$. Instead, they set $[\text{CH}_3\text{CH}_2\text{COO}^-] = [\text{CH}_3\text{CH}_2\text{COOH}] = 0.20 \text{ M}$, resulting in $K_a = 1.6 \times 10^{-3}$
- Calculating a new $[\text{CH}_3\text{CH}_2\text{COOH}]$ instead of using the molarity given in the question
- Miscalculating $[\text{H}_3\text{O}^+]$ from the pH
- Difficulty solving $10^{-2.79}$ on the calculator
- Confusing natural log with base 10 log
- Using moles in place of molarity
- Rounding the hydronium ion concentration to one significant figure, resulting in an incorrect K_a value
- Omitting $[\text{CH}_3\text{CH}_2\text{COO}^-]$ from K_a when substituting
- Not squaring the value of $[\text{H}_3\text{O}^+]$ in the K_a expression
- Incorrectly using the calculator, resulting in a K_a value off by a power of 10

Part (c)(i): Successful students recognized the solution as the same as that present at the equivalence point of the titration of a weak acid with a strong base, or as the simple solution of a weak base that hydrolyzes in water. These students correctly justified their disagreement with the statement given in the prompt. Others either incorrectly agreed with the prompt statement (e.g., stating that mixing equal moles of acids and bases always resulted in a $\text{pH} = 7.0$ solution), or they disagreed but gave an inaccurate justification by either:

- Citing that the strong base overpowered the “weak” acid
- Stating that the strong base completely dissociates but the weak acid does not
- Stating that OH^- only reacts with H^+ (or H_3O^+) in solution and not $\text{CH}_3\text{CH}_2\text{COOH}$
- Noting that excess hydroxide ion from NaOH caused the basic pH instead of the propanoate ion hydrolysis
- Not recognizing hydrolysis of the conjugate base
- Stating that the solution was a buffer
- Stating that weak acids are not able to neutralize strong bases

- Stating that strong bases dissolve and weak acids do not
- Identifying NaOH as an acid or CH₃CH₂COOH as a base

Part (c)(ii): Some students correctly agreed with the prompt statement, but they failed to adequately justify their agreement by:

- Confusing the terms dissociation and dissolving and stating that HCl dissolves completely while CH₃CH₂COOH does not
- Discussing the complete ionization of HCl but not comparing this to the ionization of CH₃CH₂COOH

Other students incorrectly disagreed with the prompt statement, justifying their disagreement by:

- Stating that if the pH is the same, the molar concentration must be the same
- Stating that molar concentration does not affect pH
- Relating acidity to number of hydrogen atoms in the molecular formula
- Relating acidity to molar mass

Part (d): Successful students earned 2 points in part (d) by recognizing that at the equivalence point in an acid-base titration, moles_{acid} = moles_{base}, or for realizing that, for monoprotic species, $M_{acid} \times V_{acid} = M_{base} \times V_{base}$. Students who failed to earn the points in part (d), did so by:

- Dividing by total volume
- Using 0.050 L as the volume of acid
- Attempting to use the Henderson-Hasselbalch equation
- Reversing the volumes of acid and base solutions
- Calculating moles of base and then attempting to use the K_a of propanoic acid to find [H⁺]
- Calculating [H⁺] as 0.142 M and then using the K_a expression to solve for [CH₃CH₂COOH]
- Not realizing mol NaOH = mol CH₃CH₂COOH and performing two separate mole calculations
- Calculating moles but reporting moles
- Rounding moles to one significant figure, resulting in incorrect molarity
- Not being consistent with volume units
- Incorrectly converting mL to L

Part (e): Students demonstrated their misunderstanding of indicator choice in an acid-base titration by:

- Comparing different values (such as pH to pK_a or pK_a to K_a) to support their claim
- Ignoring the answer in part (b) and making an inconsistent claim
- Justifying without numerically comparing values
- Comparing close K_a or pK_a values and declaring them as significantly different to support the student's claim

Based on your experience of student responses at the AP[®] Reading, what message would you like to send to teachers that might help them to improve the performance of their students on the exam?

Suggestions for teachers:

- Require students to show work and methods for solving problems, stressing process over memorization.
- Provide opportunities for students to write statements of explanation using correct scientific vocabulary and reasoning, using evidence to support their claims, giving concise answers, and writing legibly.

- Make sure students distinguish between amount (moles) and concentration (molarity).
- Demonstrate tools such as “ICE” or “RICE” tables when solving equilibrium problems and stoichiometry problems.
- Provide students opportunities to calculate molarity of an unknown acid or base using stoichiometry.
- Provide true and false statements and ask students to support answers with chemically valid reasons that are clearly written and concise.
- Use particulate images and/or animations to show strong vs. weak, initial concentrations vs. ion concentrations.
- Provide multiple laboratory opportunities for students to perform titrations between strong and weak acids/bases and devote time to discussion of properties of titration curves (be sure to discuss “why” the pH at equivalence is not always 7).
- Demonstrate the use of different indicators with a variety of weak acids.

Suggestions for students:

- Be sure that numerical answers are reasonable.
- Show work clearly and label all numbers with appropriate units.
- Write charges on all ions.
- Differentiate between moles and molarity in calculations.
- Use the calculator for all calculations; learn how to calculate logarithms (base 10 vs. natural log).
- Follow the written instructions to respond to the question on the lined pages provided and not in the question unless it is specifically requested (e.g., completing a diagram).
- Round calculations to appropriate significant figures.
- Write clearly.
- Do not rewrite/restate the question using valuable time.
- Answer questions legibly, precisely, and concisely.

Question 3

What was the intent of this question?

Question 3 covered a variety of concepts relating to electrochemistry. Students were given a labeled diagram and a description of a standard galvanic Sn/Cu cell, and told about the changes in the masses of the electrodes as the cell operated.

- In parts (a) and (b), students were asked to identify, based on observations, the electrode at which oxidation occurred, and to explain the observed change in mass at the Sn electrode.
- In part (c) students were asked to show (on a provided diagram) the particle-level flow of ions in the salt bridge.
- In part (d), students were asked how the concentrations of the ions in the cell related to the potential and total energy provided by the cell.
- In part (e), students were asked to give the net ionic equation, E_{cell}° , and ΔG° for the same reaction under different conditions, and to relate these values to the thermodynamic favorability of the process.

How well did students perform on this question?

The mean score on Question 3 was 3.33 out of a possible 10 points. Student responses covered the entire range of possible scores, with points also well distributed across all parts of the question. In general, points were most typically earned in parts (a), (c), and (e) (and hardest to earn in parts (b) and (d)). Many papers earned a point in part (a) for correctly linking oxidation to the loss of mass at the anode. Many papers

earned some or all points in part (e), even if no previous points were earned. Most students approached this question (only 3 percent of students omitted the question).

What were common student errors or omissions?

Part (a):

- Many students correctly assigned oxidation to the Sn half-cell and connected that assignment to the observed decrease in mass (or increase in mass of the Cu electrode), earning one point. However, it was very common for these answers to *incorrectly* attribute the loss of mass to the loss of electrons (such responses did not lose the point in part (a) because that point was assessed in part (b) — see below).
- Many responses correctly assigned the oxidation and reduction half-cells, but did not “explain . . . based on the student’s observations” as instructed.
- A number of responses were based on such (incorrect) general statements as “the anode always loses mass.” This by itself was insufficient to earn the point, but these responses could earn credit if the student also explicitly stated that the Sn electrode was losing mass (or Cu electrode was gaining mass).
- While some responses used the calculated E° to justify assigning oxidation to the Sn electrode, few of these explicitly made the link to observation (“the cell operates, so this is the spontaneous reaction”), so the second approach in the rubric was rarely seen.

Part (b):

- Very many students claimed the mass was going to the Cu electrode, rather than going into the $\text{Sn}(\text{NO}_3)_2(\text{aq})$ solution as Sn^{2+} ions. Students often thought that the mass lost by the Sn electrode was the same mass directly gained by the Cu electrode (some responses explicitly cited conservation of mass), and failed to notice that the ions in the separate solutions were relevant. Many students claimed that Sn^{2+} traveled through the salt bridge and plated out on the Cu electrode.
- Very many students believed electrons themselves were carrying mass from Sn to Cu, accounting for the decrease in mass of Sn and increase of Cu. Conceptually, this includes at least two major and distinct errors – both a dramatic overestimation of the contribution of electrons to the mass of chemical species, and a failure to take into account the other relevant chemistry taking place.
- The vocabulary terms “anode” and “cathode” were frequently reversed (this error was not penalized in the context of parts (a) and (b), if oxidation and reduction were properly assigned and the chemistry was correct).

Part (c):

- Typical errors included giving incorrect formulas for K^+ and NO_3^- (often dissociating these as neutral species); depicting free electrons in the salt bridge; and showing various forms of Sn and Cu ions or atoms. A large fraction of responses included no reference to KNO_3 at all.
- Approaching the “particle view” idea with circles or dots was common, and was of course accepted, but many of these omitted the charge on one or both ions, losing the point.
- In a few cases, it was clear that a student did not understand how the salt bridge diagram related to the cell diagram given above; an attempt was made in these cases to see if the response addressed the prompt appropriately, and score it without bias.

Part (d)(i):

- A majority of responses gave the (incorrect) intuitive answer, a decrease in cell potential.
- Among students who began by saying the potential would be the same in both cells, the most common incorrect justification was that E or E° is independent of concentration (and/or other conditions). Failure to distinguish between E and E° was very common.

- Some students answered in terms of Le Châtelier's principle or the value of K (though the system is not at equilibrium).
- Interestingly, although the Nernst equation is no longer given on the equation sheet, many students successfully earned this point by referring to the Nernst equation or explicitly citing it from memory, and answering on the basis that $Q = 1$ in both experiments. Since students had not written a reaction equation in this or previous responses, it was unusual for a student to refer to Q without invoking the Nernst equation.

Part (d)(ii):

- Many responses predicted that the nonstandard cell would power the device for the same length of time (usually because voltage was the same, because current was the same, or because it would be independent of concentration).
- Some predicted a longer runtime for the nonstandard cell, generally on the basis that the reaction would be slower.
- Among the responses predicting (correctly) that the nonstandard cell would power the device for a shorter time, decreased voltage was (incorrectly) commonly cited as the reason.
- Other responses explicitly pointed to something besides Cu^{2+} as the limiting reactant (e.g., Sn electrode being exhausted sooner, fewer electrons being present, salt bridge running out, etc.), or mentioned the lower concentration but did not explicitly state that fewer (moles of) ions were present.
- There were a few responses in which students seemed to interpret the question in terms of how long it would take to charge a battery for an electronic device, rather than how long the cell would provide power for the device, but these were rarely sufficiently compelling to be considered for credit.

Part (e)(i):

- Very many students earned one or both points (these were among the most commonly-earned points on low-scoring papers).
- Among responses that lost one or both points, errors were varied. Common errors included:
 - giving equations that were not net ionic
 - including free electrons on one or both sides of the equation
 - giving the two half-reactions, but not the overall equation for the redox reaction
 - reversing the reaction
 - using an inappropriate combination of half-reactions (often, all four half-reactions added together, with or without reversing some);
 - failing to reverse the Sn half-reaction (and giving a double reduction, with or without explicitly showing the electrons consumed)
 - calculating the E_{cell}° value incorrectly (including reversing the Sn reaction but then subtracting its E_{ox}°)
 - attempting to justify thermodynamic favorability in terms of ΔH and ΔS (which students had no data to support)
 - justifying thermodynamic favorability on the basis that one species was being reduced and the other oxidized
 - failing to address thermodynamic favorability at all, or failing to explicitly link it to the *sign* of E_{cell}° (rather than merely stating the value)
- Justifications based solely on the organization of the table (as in, "Cu is higher in the table, so it's reduced") did not earn the justification point.

- Some students clearly missed that the experimental setup had changed (answering in terms of separate half-cells, instead of a direct reaction), while others missed the fact that the overall reaction was still the same (selecting inappropriate half-cell reactions).
- Many responses selected the combination of half-cell reactions that gave the largest positive E_{cell}° ($2 \text{Cu}^+ + \text{Sn} \rightarrow 2 \text{Cu} + \text{Sn}^{2+}$), even though Cu^+ was not a reactant.
- While the rubric includes an alternate strategy to earn the second point by linking spontaneity to the observed operation of the cell in previous experiments, very few papers used that path.

Part (e)(ii):

- A point was quite commonly earned for the correct number of electrons (or appropriate to the student's reaction in part (e)(i)).
- Math errors, sign errors, unit errors or omissions, errors in conversion from J to kJ, etc. were common in work for the second point.
- Students who used an (incorrect) value of E° from part (e)(i) in part (e)(ii) were not penalized, but an incorrect E° value appearing for the first time in part (e)(ii) lost the second point.

Based on your experience of student responses at the AP[®] Reading, what message would you like to send to teachers that might help them to improve the performance of their students on the exam?

- Link the macroscopic observations (sign of cell voltage, loss/gain of mass, magnitude of current) to the particle-level processes (electrons being gained and lost, ions being reduced to atoms and vice versa, rate of reaction or resistance due to diffusion of ions in salt bridge.) Encourage students to think about where particles are going and how they are changing as a reaction proceeds.
- Encourage students to pay close attention to the actual question (e.g., “based on the student's observations,” “justify your answer,” “in another experiment,” “include units with your answer”) and to check again after they think they've finished the answer.
- Avoid teaching algorithmic approaches (e.g., “copper is reduced because it's higher in the table” or “the anode is on the left”) in lieu of understanding processes.
- Drill students to think about what species are actually present in solutions.
- Encourage students to think about what's going on in each part of a galvanic cell (e.g., including how the salt bridge acts as both a simple electrolyte solution, to conduct current, and as a reservoir for ions to migrate into the half-cells) and how it's different from a direct-contact redox reaction or an electrolytic cell.
- Work with students on the relationships between current (which is, ultimately, kinetically controlled) and voltage/potential (which is thermodynamically controlled), and how they relate to concentration, temperature, Q , K , ΔG , power, energy, etc.
- Point out the differences and connections between equilibrium and non-equilibrium processes, so students understand that an operating galvanic cell is (necessarily) not at equilibrium, but rather reactions are occurring to reach equilibrium.
- Point out the differences between standard and nonstandard conditions, and help students practice applying the appropriate equations, values, and concepts.
- While the Nernst equation is not explicitly included in the AP[®] curriculum, it is a useful tool for relating the behavior of standard and nonstandard cells, and clearly helped some students organize their ideas.

Question 4

What was the intent of this question?

Question 4 was designed to evaluate student understanding of a dynamic equilibrium system undergoing a reversible reaction. Students were presented with a graphical relationship of the variables pressure and time for the chemical reaction represented by: $\text{CaCO}_3(s) \rightleftharpoons \text{CaO}(s) + \text{CO}_2(g)$. This question also addressed the relationship between K_p and P_{CO_2} .

Part (a): In this part, the students were asked to apply a mathematical relationship (the ideal gas law) to a natural phenomenon (decomposition of a solid to form a gas). Given the appropriate data, the students had to calculate one unknown variable in the ideal gas law.

Part (b): In this part, the students were asked to analyze data and construct explanations of phenomena based on experimental evidence presented in graphical form. Data from two experiments were presented and students were asked to agree or disagree with a student claim based on the given data. Students had to recognize and explain that the decomposition had not gone to completion and conclude that the system was at equilibrium. Students could use either mathematical or nonmathematical explanations to refute the claim in the question.

Part (c): In this part, the students were asked to evaluate the effect on the equilibrium when additional $\text{CO}_2(g)$ was injected into the system. Students were expected to claim, based on knowledge of scientific theories, whether the final pressure would be less than, greater than, or equal to the pressure at equilibrium and to give a rationale for their prediction.

Part (d): In this part, students were asked to determine if sufficient experimental data had been obtained to determine the value of K_p . To receive credit they had to justify their answers.

How well did students perform on this question?

The mean score was 1.09 out of a possible 4 points.

What were common student errors or omissions?

One point could be earned in each part for a total of four points.

Part (a): This was the only mathematical problem in this question. Therefore, no credit was earned for miscalculation, but incorrect use of significant figures was not penalized. To earn credit, students had to show their work.

Common student errors or omissions included:

- Using an incorrect R value to calculate the moles of gas in the ideal gas law relationship
- Inverting the gas law variables
- Confusing “ T ” for time rather than temperature in $PV = nRT$
- Equating 22.4 L to 1 mol for a system that was not at standard temperature and pressure (STP)
- Making mathematical mistakes
- Failing to recognize this as an equilibrium system. Thus, calculating the moles of $\text{CO}_2(g)$ using the stoichiometric ratio in the balanced equation and the given amount of $\text{CaCO}_3(s)$, either 50 g or 100 g
- Estimating the pressure of the $\text{CO}_2(g)$ from the graph rather than using the given value

Part (b): In this section, students were asked to evaluate the claim that all the $\text{CaCO}_3(s)$ was completely decomposed in this system. Although the question asks, “do you agree with this claim?”, answers “yes”/“correct” or “no”/“incorrect” are considered equivalent to “agree” or “disagree” respectively. For credit, “disagree” had to be correctly explained.

There were two acceptable explanations that show the creation of an equilibrium condition:

Explanation I: *mathematical calculation* using stoichiometry to show that the number of moles of gas that could be obtained by the total decomposition of 50 g of solid was greater than the actual number of moles of gas calculated in part (a)

Explanation II: *on mathematical discussion* of the evidence of formation of an equilibrium system such as doubling the amount of solid did not affect the pressure

Common student errors or omissions included:

- Failing to give an explanation based on data, such as:
 - Explanation based on time of decomposition
 - Explanation based on rate of decomposition
 - Explanation based on the definition of equilibrium
 - Explanation based on double arrow in chemical equation
- Simply stating that the pressure had “leveled off” was insufficient (To earn a point, students had to provide an explanation based on one of the two explanations above.)
- Stating that equilibrium was established because the final pressure was constant
- Describing a dynamic equilibrium with no reference to data

Part (c) Students had to use Le Châtelier’s principle (or similar discussion) to predict and explain the direction of a shift caused by the addition of the gaseous product in the reaction. Students had to predict “less than”, “greater than”, or “equal to 1.04 atm”. Only “equal” received credit with an explanation based on Le Châtelier’s principle. Explaining the shift toward the reactant without mentioning Le Châtelier’s principle was also sufficient.

Common student errors or omissions included:

- Disregarding the data given for injection of additional $\text{CO}_2(g)$
- Failing to explain the equilibrium shift
- Simply stating, “When more $\text{CO}_2(s)$ is added, the pressure will remain constant” was an insufficient explanation
- Illustrating or describing the shift toward the products rather than toward the reactant
- Discussing collision theory and/or reaction rates
- Answering “yes” or “no”

Part (d): Students were expected to recognize that the question contained sufficient data to calculate K_p and explain the relationship between K_p and the pressure of the gas in the system. To be able to earn credit, students had to have described part (b) as an equilibrium system.

Note: If a student answered “Agree” in part (b), meaning that the $\text{CaCO}_3(s)$ had completely decomposed, one point could be earned in part (d) for explaining that there were insufficient data to calculate the K_p in a nonequilibrium system.

Common student errors or omissions included:

- Failing to recognize that K_p was determined solely by the pressure of gaseous species in the system

- Including solids in the equilibrium expression and equating this to K_p
- Failing to recognize that complete decomposition of $\text{CaCO}_3(s)$ does not create an equilibrium system
- Calculating the molarity of all species and using these values in an equilibrium expression.
- Simply giving the expression for K_p from the formula sheet

Based on your experience of student responses at the AP[®] Reading, what message would you like to send to teachers that might help them to improve the performance of their students on the exam?

- Students should read questions carefully and use given data to support their explanations.
- For credit, students should show the setup for answering quantitative questions.
- Students should understand the dynamics of an equilibrium system, and be able to:
 - Use experimental data to identify when a system is at equilibrium.
 - Explain how a system reacts when it is stressed.
- Teachers should provide examples for students to practice solving data-based problems.
- Teachers should ask students to justify claims with evidence from experimental data.
- Students should use stoichiometric (mol) ratios to justify answers when appropriate.
- Students should learn the difference between commonly used chemistry vocabulary such as “decomposition” and “dissolution” (liquid was not present in this question).

Question 5

What was the intent of this question?

Question 5 was designed to explore student understanding of atomic and molecular structures, with specific reference to periodic trends. In part (a) students had to observe a periodic trend in the molecular formulas of fluorine compounds and apply a given hypothesis to predict the formula of a chlorine fluoride compound. In part (b) students had to complete a Lewis electron dot diagram for chlorine trifluoride. In part (c) students had to choose whether chlorine trifluoride is trigonal planar or T-shaped based on its measured nonzero dipole moment. In part (d) students had to propose a modification to a simple hypothesis based on an extended list of formulas of known halogen fluorides.

How well did students perform on this question?

The mean score for Question 5 was 1.67 out of a possible 4 points.

What were common student errors or omissions?

Part (a): Many students wrote a chemical formula that ignored both the given trend and the stated hypothesis. Others wrote about the mathematical hypothesis but gave no resulting formula.

Part (b): Within the Lewis electron-dot diagram, some students did not include some or all of the electrons in lone pairs around the fluorine atoms and/or did not include one or both lone pairs of electrons around the central chlorine atom. Some students placed lone pairs so close to bonding pairs that it appeared to imply a multiple bond, while others overtly included double bonds between the chlorine atom and one or more of the fluorine atoms.

Part (c): Some students stated “T-shaped” without justification or indication that asymmetric electron distribution leads to overall molecular polarity. Some students explained why the molecule is T-shaped rather than indicating why T-shaped is polar. Some students referred to “uneven sharing of electrons” without distinguishing between polar covalent bonds and overall charge distribution.

Part (d): Many students just restated the original hypothesis. Some students failed to observe that or explain why additional fluorines around the central halogen must come in pairs (resulting in odd numbers of fluorines as each lone pair of electrons around the halogen is split to make individual electrons available to form two new covalent bonds). Others did not observe the periodic characteristic that the number of possible fluorines on each halogen increases as the valence shell increases in size with each period. A few students confused “period” with “group” when attempting to describe periodicity.

Based on your experience of student responses at the AP[®] Reading, what message would you like to send to teachers that might help them to improve the performance of their students on the exam?

Students who have learned about Valence Shell Electron Pair Repulsion (VSEPR) Theory should have discussed the logic that might lead one to select, for a species such as ClF_3 with a total of five electron pairs around the central atom, a trigonal bipyramidal structure rather than a trigonal planar configuration. Prediction of the trigonal planar configuration with two axial lone pairs of electrons is a popular misconception. For the combination of five pairs of electrons around the central atom (three bonding pairs and two lone pairs), a T-shaped molecular geometry is preferable since the two nonbonding pairs of electrons will repel each other and assume positions in the equatorial plane ($\sim 120^\circ$ apart from each other and 90° from each axial electron pair) rather than trigonal planar positions (two nonbonding electron pairs in axial positions, three bonding electron pairs in equatorial plane). The latter configuration places each lone (nonbonding) pair of electrons at 90° to three other electron pairs in the equatorial plane, which allows more interaction (repulsion) between electron pairs and leads to a more unstable configuration. Students who have built models in laboratory or explored a guided-inquiry learning activity might be more apt to remember these ideas than students who have memorized a table listing different possibilities of grouping electron pairs as bonding or nonbonding (lone electron pairs) around a central atom, so teachers should consider these alternative ways of presenting the topic.

Other students understood the concept of orientation of bonding and non-bonding pairs of electrons but were unable to convey adequately *why* a molecule is polar. They may have memorized that a given geometry leads to a polar molecule but not why the dipole occurs. Students should be encouraged to learn more about how the geometry leads to polarity, that symmetrically arranged dipoles cancel, and that regions of partial charge separation (δ^+ and δ^-) on the entire molecule cause an observable dipole moment.

Question 6

What was the intent of this question?

Question 6 integrated the concepts of physical properties of compounds and heats of reaction. Propene and the polymer polypropylene (PP), and chloroethane (vinyl chloride) and the polymer polyvinyl chloride (PVC) were compounds used in this question. Knowledge of the relationship of mass to volume (density) was needed to answer part (a) to determine which polymer would sink relative to water. For part (b) knowledge of differences in electronegativity, polar bonds, dipole moment, size of the electron cloud, and polarizability was needed to determine the intermolecular forces possible for a given molecule. Once the kinds of intermolecular forces were determined for each molecule, a comparison of relative strengths of those intermolecular forces was needed to explain the given differences in boiling points. Specifically, students had to recognize the presence and strength of London dispersion forces or dipole-dipole forces of attraction among molecules of the two substances in order to explain the difference in their boiling points. In part (c) students had to calculate the ΔH° for the combustion of 2 moles of propene, to compare that calculated value to the given ΔH° for the combustion of 2 moles of vinyl chloride, and to decide which combustion released more energy.

How well did students perform on this question?

The mean score was 1.47 out of a possible 4 points. Students generally attempted all parts of the question. If a part was omitted it was usually part (b). Of the points missed, the most common were in parts (a) and (b). A score of 1 often was for the calculation of the ΔH° for 2 moles of propene.

What were common student errors or omissions?

Part (a): Successful students concluded the PVC beads sink because they have a higher mass in a similar volume, making them denser. Other students found a wide variety of reasons why PVC (or PP) beads should sink. Some of these reasons included:

- Citing solubility as the reason for sinking (e.g., the beads dissolve in water)
- Citing bonding of the PVC to water as the reason for sinking
- Citing intermolecular forces as the reason for sinking (e.g., the beads hydrogen bond to water)
- Trying to use a polar/nonpolar argument for sinking (e.g., PP is nonpolar and will not sink in water)
- Claiming that vinyl chloride is an ionic compound and thus the Cl ionizes in water
- Comparing size rather than mass differences between CH_3 and Cl (e.g., CH_3 is larger and PP sinks)
- Comparing only CH_3 group of PP to water (e.g., CH_3 is less dense than water)
- Comparing only the Cl atom of PVC to water (e.g., Cl is denser than water)
- Writing that “PP is smaller” instead of “PP has a smaller molar mass.”

Part (b): Successful students referred to either higher LDFs (because of the larger, more polarizable electron cloud) and/or higher dipole-dipole forces (because of the larger dipole moment) among vinyl chloride molecules as the reason for its higher boiling point. Other students failed to earn the point by:

- Confusing intermolecular forces (dipole-dipole or LDFs) with *intramolecular* forces (covalent bonds)
- Citing *molecular properties* instead of *intermolecular forces* (i.e., dipole moments instead of dipole-dipole attractions, or polarizabilities instead of induced dipole-induced dipole attractions)
- Using abbreviations of terms that are not accepted abbreviations (e.g., D-D, DP-DP for dipole - dipole (note: LDF for London dispersion force is widely accepted, so it is OK))
- Stating that it is mass that determines the magnitude of London dispersion forces, rather than the accurate reference to larger, more polarizable electron clouds
- Stating that the bonding within a molecule (C- CH_3 , C-Cl) determines intermolecular forces
- Stating that vinyl chloride is an ionic compound, thus there are ion-dipole intermolecular forces of attraction
- Stating that intermolecular forces are greater, but never identifying any specific intermolecular force
- Claiming that there is hydrogen bonding in the polymer molecules
- Drawing pictures of parts of the molecule and not being able to decide if the picture represents hydrogen bonding or dipole-dipole attractions ($\text{H}^+ \cdots \text{Cl}^-$).
- Assuming that boiling is the result of intramolecular bond breaking (breaking bonds is not the same as overcoming intermolecular forces)

Part (c): Successful students correctly applied Hess's law to determine the enthalpy of combustion of two moles of propene and compared their value to the corresponding value for 2 moles of vinyl chloride to conclude that propene combustion releases more energy. Other students failed to earn one or both points by one or more of the following errors:

- Thinking that this was a bond enthalpy question and using $\Delta H^\circ = \text{Bonds broken} - \text{bonds formed}$.

- Making transcription errors when copying numbers from the table (mainly using vinyl chloride value when propene value was needed)
- Making algebra errors when parenthesis are involved
- Making arithmetic (addition and subtraction) errors.
- Multiplying or dividing by 2 the calculated value for ΔH° of propene because the question asked for the value for 2 moles of propene. The thermochemical equation given was for 2 moles so the calculation was for the mole-reaction. There was no need to multiply or divide the number calculated.
- Misunderstanding when to and when not to use a sign for a thermochemical equation
 - $\Delta H^\circ = -3858 \text{ kJ}$, thus 3858 kJ energy released
 - $-3858 \text{ kJ} > -2300 \text{ kJ}$ in terms of the magnitude of heat released

Based on your experience of student responses at the AP[®] Reading, what message would you like to send to teachers that might help them to improve the performance of their students on the exam?

- Students should read the questions more carefully.
 - Table values were often plugged in incorrectly.
 - The heat of combustion for vinyl chloride was given twice in the stem of the question, yet students often tried to calculate that value.
- Chemistry uses a very **specific set** of vocabulary words and terms. Students need to be able to understand the meaning of the words and then use them accurately in answering numerical and essay questions. This is especially true for intermolecular forces. Often confused and or misused terms include:
 - Intramolecular bonds within a molecule
 - Intermolecular forces between molecules
 - Polar bonds
 - Dipole moment
 - Dipole–dipole intermolecular attractions
 - Molar mass
 - Nonpolar bonds
 - Electron density
 - Polarizability
 - London dispersion forces
 - Induced dipole–induced dipole forces
- When writing about IMFs, students need to be very careful to describe the forces for the entire molecule and not just write about a single atom or a particular bond in the molecule, because this makes it hard for the scorer to distinguish between intermolecular and intramolecular arguments (e.g., if question involves the polarizability of a molecule, then reference to just one atom in the molecule is not sufficient).
- If students are given a choice of answers (releases more, less, or the same), they should use one of those terms in their answer.
- Students need to understand the concepts and go beyond the mere plug and chug algorithmic approach to answering questions.
- As stated in the directions for the free-response questions, if asked for a calculation, to earn credit one must show the setup for that calculation. Just a number written down will not earn the calculation point.
- Comparing the heats of combustion for propene and vinyl chloride was more of a challenge. Understanding that the negative sign is a convention for heat released was less commonly understood. Some students said that $-3858 \text{ kJ/mol}_{\text{rxn}}$ was less heat released than $-2300 \text{ kJ/mol}_{\text{rxn}}$.

- When presented with evidence about two chemical species, students should be sure to include information and reasons for each of the species when drawing their conclusions. This applied to part (a) and part (b) of the question.

Question 7

What was the intent of this question?

Students were required to interpret kinetic data in the isomerization reaction of *cis*-2-butene to *trans*-2-butene under various conditions in the gaseous state. Four trials were presented in a table that listed the initial pressure of *cis*-2-butene, the volume of the reaction chamber, temperature, and half-life of the reaction. Part (a) stated that the reaction is first order and asked for an explanation of how the data was consistent with this fact. In part (b) students calculated the rate constant k for the reaction at 350 K. Part (c) assessed students' knowledge of the relationship between reaction rates, rate constant, and concentration by asking for a prediction, with justification, about whether the initial rate of reaction in trial 1 would be greater than, less than, or equal to that in trial 2. (Relative to trial 1, trial 2 had an identical volume, temperature, and half-life, but twice the initial partial pressure of reactant.) In part (d) students needed to explain why, in terms of activation energy, the half-life of the reaction in trial 4 is less than its half-life in trial 1. This part examined the ability to logically associate a higher temperature with greater average kinetic energy of reactant molecules and thus a greater fraction of molecules able to collide with enough energy to overcome the activation energy barrier to reaction.

How well did students perform on this question?

The mean score was 0.43 out of a possible 4 points. The majority of students who earned no points did address one or more parts of the question. Part (b) was the most frequently attempted section of this question, but responses often did not earn a point due to missing or incorrect units at the end of the calculation.

What were common student errors or omissions?

Generally:

- Using the terms half-life, rate constant, and reaction rate incorrectly or interchangeably
- Occasionally referring to equilibrium constant, K , rather than rate constant, k

Specifically:

Part (a): Successful students realized that first order reactions at a given temperature have a fixed half-life. Others demonstrated their misconceptions in a number of ways but primarily by conflating reaction rate and half-life. Specific examples include:

- Concluding that the reaction was zeroth order, in direct contradiction of the statement in the question that the reaction was first order (Zeroth order reactions have a half-life that is dependent upon the initial concentration of reactant, whereas first order reactions do not.)
- Confusing the dependent and independent variables in the data table, e.g., "When the reaction was run at shorter half-life in trial 4, the temperature increased."
- Providing answers that were factually incorrect, overly general, or insufficiently connected to specific data from the table -- commonly, students claimed that the reaction was first order because:
 - From trial 3 to trial 4, reducing the concentration of reactant by a factor of two caused the half-life also to be reduced by a factor of two.
 - Only first order reactions have a half-life.
 - Varying the temperature changed the half-life of the reaction.
 - The equation $t_{1/2} = 0.693/k$ was obeyed in all trials.

- The ideal gas law applies to all trials, and/or citing examples of 1:1 changes in pressure:volume ratios
- A plot of $\ln[\text{cis-2-butene}]$ versus time will be linear.
- In the rate law equation for the reaction, the exponent for $[\text{cis-2-butene}]$ is 1.

Part (b): Successful students realized that there is a fixed relationship between the half-life of a first order reaction and its rate constant. They correctly applied the equation (given in the exam equations) to find the first-order rate constant. Other students failed to see the relationship or made typical computational mistakes:

- Committing errors in mathematical setup, e.g., $0.693 \times 100 \text{ s}$ or $100 \text{ s} / 0.693$ rather than $0.693 / 100 \text{ s}$
- Reporting an incorrect order of magnitude, e.g., 0.0693 s^{-1} or 0.000693 s^{-1}
- Using incorrect units or omitting units entirely (The responses with correct units often showed units appropriately in the intermediate mathematical setup.)

Part (c): Successful students realized that to consume half the amount of reactant in the same time required half the initial rate (in trial 1 vs. trial 2). Other students failed to earn the point by:

- Stating only that the initial pressure of the reactant is lower in trial 1 than in trial 2, without any corroborating mention of quantities related to the reaction rate law such as concentration, partial pressure, or moles of reactant per unit volume
- Claiming that reaction rate is dictated by the number of moles of reactant present, as opposed to the concentration or partial pressure of the reactant
- Proposing that the initial reaction rates were identical because the half-lives in trial 1 and 2 were equal, or because both trials were conducted at the same temperature
- Failing to specify which trial was being referenced in the response
- Making claims that were factually true, but not responsive to the question

Part (d): Successful students realized that at higher temperature a greater fraction of molecular collisions has sufficient energy to overcome the activation barrier. Other students failed to earn the point by:

- Failing to connect macroscopic measurements (temperature and half-life) to events at the molecular level (increased population of particles having sufficient energy to overcome an activation barrier, according to the collision model in kinetic molecular theory)
- Believing incorrectly that the potential energy surface of the reaction changes as a function of temperature:
 - “The activation energy becomes lower as temperature is increased.”
- Incorrectly referring to heat as a catalyst
- Mistakenly defining activation energy as the amount of thermal energy available in a reaction, as in “There is more activation energy in trial 4 than in trial 1.”
- Referring to the Arrhenius equation, stating that the rate constant for a reaction increases with temperature (While true, the Arrhenius equation *describes how* the rate constant increases with temperature, but it does not *explain why* the rate constant increases with temperature.)
- Explaining with incomplete or over-generalized reasoning — some common claims that appeared alone, without any further justification:
 - Reactions always proceed faster at higher temperatures.
 - More energy is available at higher temperature.
 - Particles move faster at higher temperature.

Based on your experience of student responses at the AP[®] Reading, what message would you like to send to teachers that might help them to improve the performance of their students on the exam?

- Provide students with opportunities, both verbally and in writing, to use chemical terminology and their corresponding mathematical representations correctly — especially with terms like “reaction rate,” “rate constant,” and “half-life” that are interconnected but have different meanings. Mistakenly using “number of moles of reactant” interchangeably with “concentration of reactant” to describe influences on chemical kinetics was another common error in this question.
- Help students to identify the difference between reciting a fact (which is often insufficiently responsive) versus providing a direct and comprehensive explanation of a phenomenon. In part (d), for example, connecting macroscopic measurements to kinetic molecular theory is a more complete explanation than a general statement about reactions proceeding faster at higher temperature.
- Provide opportunities for students to practice giving detailed explanations that are connected to theoretical and/or particulate-level reasoning.
- Address the common misconception that raising the temperature of a system lowers the activation energy of a reaction.
- Show how the wording of questions contains cues for the most appropriate response. For example:
 - Part (a) states that the reaction is first order, so any attempt to argue otherwise would be unfruitful.
 - Part (b) specifically asks for appropriate units, so that information will likely factor into the scoring.
 - Since part (c) asks about the initial rate in trial 1, the response is most clearly framed by describing trial 1 first.
 - Part (d) asks for an explanation based on activation energy, so that term is likely to appear in the correct answer.
- Include units with every individual term in a mathematical equation, even in the setup, to avoid simple errors. Careless mistakes often occur when units are assigned arbitrarily at the end of a calculation.
- Encourage the use of precise, specific language that avoids ambiguity:
 - The use of pronouns should be minimized so as to enhance clarity.
 - Vague statements like “Some values change while others remain constant” are difficult to interpret.
 - Refer specifically to data by naming the variable, numerical value, trial number, etc.
- Emphasize the importance of clear, legible handwriting.