CollegeBoard AP

Student Performance Q&A:

2009 AP® Chemistry Free-Response Questions

The following comments on the 2009 free-response questions for AP® Chemistry were compiled by the Chief Reader, Eleanor Siebert of Mount St. Mary's College in Los Angeles, California. 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?

This question assessed the breadth of students' understanding of weak acid/weak base/buffer equilibria in aqueous solution and their ability to apply the concepts to solve problems. In part (a)(i) students were required to interpret given K_a values of two halogen oxoacids to determine their relative acid strengths. In part (a)(ii) students were asked to draw a complete Lewis electron-dot diagram for one of the halogen oxoacids, and in part (a)(iii) they had to predict and justify the relative strength of a third oxoacid in terms of principles of chemical bonding. In part (b) students were asked to write a balanced chemical equation for the reaction of a weak acid in aqueous solution. In part (c) they were required to write a hydrolysis expression, calculate the value of K_b (hydrolysis equilibrium constant) from the given value of K_a, and calculate $[OH^-]$ for a solution of the conjugate base of one of the oxoacids of given concentration. Finally, in part (d) students had to determine $[H_3O^+]$ in a buffer solution of given pH and to apply the definition of K_a (or the Henderson–Hasselbalch equation) to determine the relative concentrations of HOCl and OCl^- in the buffer solution.

How well did students perform on this question?

Students performed well on this question. The mean score was 4.46 out of 10 possible points. Students typically earned the most points on parts (a)(i), (a)(ii), (b), (c)(i), and (d)(i). With the exception of the calculation of pH in part (d)(i), these parts were not quantitative and required students to apply general chemical principles. A large percentage of students earned 4 or 5 of the points on these five parts but earned no points on the remaining parts of the question.

Students found parts (c)(ii) and (c)(iii) to be challenging but were often able to earn some of the points available. Many students answered part (d)(ii) correctly, using a range of quantitative justifications. Part (a)(iii) was the most difficult part on which to earn credit because it required students to clearly explain the effect of halogen substitution on the acid strength; many student responses to this part were vague and disorganized. Overall, the question seemed to work well, contained a good distribution of accessible and challenging points throughout, was appropriate in content and level of difficulty, and discriminated effectively among students on the basis of their understanding of aqueous equilibrium chemistry. There also was good variety in the student responses.

What were common student errors or omissions?

Part (a)(i). The great majority of responses answered this part correctly. Common errors included:

- Failing to address the relative acid strength in terms of K_a
- Ranking incorrectly the numerical values of K_a given in scientific notation
- Associating greater K_a values with weaker acids
- Using the terms pK_a and pH interchangeably

Part (a)(ii). Most students earned credit on this part. Common errors included:

- Placing halogen or hydrogen as the central atom
- Using incorrect/excess numbers of electrons, including full octets surrounding the hydrogen atom
- Replacing lone pairs of electrons with double and/or triple bonds
- Drawing ionic structures

Part (a)(iii). This was the most infrequently earned point. Common errors included:

- Predicting incorrectly that HOI would be stronger than HOCl
- Predicting acid strength on the basis of periodicity
- Attributing the relative strength to atomic size, orbital occupancy, general reactivity, or other factors
- Stating that iodine has a lower electronegativity than chlorine but failing to indicate how this would affect the acid strength
- Attributing electronegativity to the molecule or to the bonds rather than to atoms
- Using vague language: writing "strong bonds," "strong acids," or "strong electronegativities" without the precision necessary to answer the question correctly
- Attributing relative acid strength to hydrogen bonding, dispersion forces, polarity, or other intermolecular forces
- Exhibiting confusion between *dissociation* and *dissolving*, and consequently, *acid strength* and *solubility*

Part (b). Most students answered this part correctly. Common errors included:

- Writing the formula for an acid that is different from hypochlorous acid (e.g., HCl, $HClO_2$, $HClO_3$, and $HClO_4$ were most common)

- Including the role of the water on one side of the equation but omitting it on the other side, resulting in an unbalanced equation
- Omitting charges on ionized species
- Including incorrect product species, such as OH^-, H_2, and H_2O_2

Part (c)(i). Most students answered this correctly. Common errors included:

- Failing to write the correct charge on species
- Including $[H_2O]$ in the equilibrium constant expression

Parts (c)(ii) and (c)(iii). These parts proved challenging for students. Common errors included:

- Using the concentration of the NaOCl solution given as 1.2 *M* in part (c)(ii) to determine the value of $K_b(OCl^-)$
- Using the value of K_a in place of the value of K_b
- Calculating correct values but failing to interpret them and then going on to use them to calculate incorrect values or to label incorrect values as the intended response
- Using the incorrect relationship $K_b = \frac{1}{K_a}$
- Confusing *values* of equilibrium constants (K_a and/or K_b) with *concentrations* of species and using them interchangeably

Part (d)(i). Students who attempted this problem were generally able to solve it correctly. Common errors included:

- Failing to do the conversions correctly
- Failing to include the exponent in the concentration expression

Part (d)(ii). This was a challenging problem for most students. Common errors included:

- Attributing $[HOCl] > [OCl^-]$ to the $pH < 7$ rather than to $pH < pK_a(HOCl)$
- Confusing $[HOCl]$ with $[H_3O^+]$
- Treating the buffer solution as a weak acid solution with $[H^+] = [OCl^-]$

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?

Teachers should use the following strategies to improve student performance on questions like this:

- Have students practice using correct and precise vocabulary (e.g., atom, ion, molecule, electron, electronegativity of atom).

- Have students practice writing chemical equations and their associated equilibrium constant expressions, emphasizing the distinctions between K_a, K_b, K_{sp}, K_c, and K_p.
- Have students practice writing simple Lewis electron-dot diagrams, emphasizing the difference between ionic and covalent bonds and differences between intramolecular bonds and intermolecular forces.
- Emphasize qualitative aspects of equilibria and buffer solutions, and reasonableness of values (e.g., students should recognize that $[OH^-] = 6{,}400\ M$ or $[H_3O^+] = 10^{6.48} = 3.02 \times 10^6\ M$ are not reasonable values).
- Give students work with algebraic manipulation of equilibrium constant expressions.
- Give students calculations involving exponents and scientific notation.

Question 2

What was the intent of this question?

This question assessed students' knowledge and skills related to determining the molar mass of an unknown gas, which is one of the laboratory experiments recommended in the *AP Chemistry Course Description.* In parts (a) through (c) students were asked to analyze data by calculating the mass of the dry air in the flask at the beginning of the experiment, the mass of the flask itself, and the mass of the unknown gas. In part (d) they were expected to recognize that the conditions of the experiment were not standard and therefore a conversion of temperature to Kelvin (and possibly pressure to match the R) was required. Students had to substitute values into an appropriate equation to solve for moles and then calculate molar mass by dividing grams of unknown gas by the calculated number of moles. In part (e) students were asked to calculate the percent error for the experiment based on the molar mass calculated in part (d) and the given molar mass of CO_2. Part (f) involved error analysis: students were given two different errors and asked to decide if either error could have led to the answer reported in part (d) and to justify their choice. In part (g) students were asked to describe an appropriate laboratory method to verify the volume of the sealed flask used in the experiment.

How well did students perform on this question?

Overall, students did reasonably well when answering this question. The mean score was 4.59 out of 10 possible points.

Students were generally successful on parts (a), (b), and (c), with many earning all 3 points. Many students did a good job of using their values consistently, even when the resulting answer became unreasonable, and went on to earn 2 of the 3 points.

In part (d) students usually recognized that the temperature and pressure were not at standard conditions and converted appropriately. Some students used 22.4 L mol^{-1} to calculate moles and used their answer to calculate molar mass. This method earned only 1 of the 3 possible points for this part.

Many students were able to earn the point for part (e) by using their answer from part (d) to calculate the percent error. Some students divided the difference in theoretical and experimental values by the experimental value rather than the theoretical value and thus did not receive the point.

Part (f) was the most difficult part of the question. Each of the two errors, occurrence 1 and occurrence 2, required students to determine if the error would have caused a larger or smaller calculated molar mass and then to justify their answer. Students had difficulty expressing their ideas with clear and concise writing. Many students answered the question vaguely by using such phrases as "change the molar mass" or "affect the answer"; these responses earned no credit. Occurrence 2 was often misinterpreted when students applied $PV = nRT$ incorrectly and came to an erroneous conclusion.

In part (g) many students earned the point for a valid laboratory method of determining volume. Some students identified a beaker or a volumetric flask as a piece of glassware that could be used to measure 843 mL and did not receive the point.

What were common student errors or omissions?

Part (a). Students often calculated the mass of the dry air correctly. Common errors included:

- Using the ideal gas equation to calculate moles and then not knowing what to do next
- Dividing the mass of the sealed flask and dry air by the density of dry air and recording the result as the mass of the dry air

Part (b). Students often correctly calculated the mass of the flask to the correct number of significant figures. Common errors included:

- Omitting the last zero in the number 157.70 g from the data table and rounding the answer to one decimal place
- Rounding the answer to a whole number (three significant figures)

Part (c). Students often calculated the mass of the unknown gas correctly. A common error was:

- Subtracting the mass of the sealed flask with air from the mass of the sealed flask with the unknown gas

Part (d). Students frequently earned 2 of the 3 points possible for this part. Common errors included:

- Failing to recognize nonstandard conditions and using 22.4 L mol^{-1} to calculate moles and then molar mass
- Substituting into the ideal gas equation but rearranging and/or calculating incorrectly
- Substituting either 1.0 atm or 298 K into the equation
- Neglecting to convert the pressure for the value of R chosen

Part (e). Students often earned the point for calculating a percent error. Common errors included:

- Calculating percent yield instead of percent error
- Dividing the difference between theoretical and experimental values by the experimental value rather than the theoretical value

Part (f). This was the most difficult part of the question for a majority of students, many of whom addressed only one occurrence (perhaps these students thought they were to choose one of the two occurrences to address). Other common errors included:

- Occurrence 1
  - Identifying that the "mass" would go down but not justifying this change by mentioning the mixture of the dry air (which is less dense than CO_2)
  - Providing vague answers—such as "will alter," "will skew," or "will throw off the results"—without committing to an increase or decrease in molar mass
  - Attributing the error to the student's fault
  - Assuming that dry air exists in addition to the CO_2, resulting in a larger mass

- Occurrence 2
  - Ignoring the fact that at lower temperatures gases become more dense
  - Stating correctly that if the temperature is decreased, then the number of moles increases but then applying the logic that since molar mass = g mol^{-1}, molar mass will decrease with an increase in number of moles
  - Providing vague answers or thinking that temperature would not alter the experimental result
  - Using various gas laws to describe pressure changes and not addressing molar mass

Part (g). Many students answered this question correctly. Common errors included:

- Failing to mention an appropriate piece of glassware with which to read the volume of 843 mL
- Stating that a volumetric flask could measure the 843 mL directly
- Using a simple water displacement method to find the volume of the flask
- Describing a method, such as one similar to the original experiment, that depends on knowing the volume of the flask
- Using the mass of the flask filled with a known gas and subtracting the mass of the empty flask, failing to recognize that an "empty" flask would contain air

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?

- Have students perform and review the recommended laboratory experiments.
- Provide opportunities for students to engage in error analysis discussions. They should examine possible errors and their effects on the outcome. When grading lab reports, be sure the student's error analysis corresponds to the error in the data.
- Engage students in laboratory activities that allow them a chance to design and redesign an experiment in order to reduce errors in the laboratory. Remind students that the steps of a laboratory procedure are not just calculations that will be performed.
- Be sure that proper equipment is used in the laboratory and that students are recording values to the correct number of significant figures when measuring.

- Work through calculations, making sure that students understand why each step of the calculation is reasonable and legitimate. Review and consistently apply rules for significant figures, especially for addition and subtraction, with laboratory data.
- Examine data analysis questions and allow time for students to decide what information is relevant, and what is extraneous, in order to perform the calculation requested.
- Have students answer “yes” or “no” and then follow with a discussion when answering a question like the one in part (f).
- Remind students that if they give more than one answer, and one is right and one is wrong, no credit is earned.
- Provide opportunities for students to write explanations and revise their writing.
- Never accept calculated answers that do not show clearly organized work.
- Be sure that all students are equipped with a working calculator for the AP Exam.
- Stress that good penmanship and clarity are important in communication.

Question 3

What was the intent of this question?

This question tested students’ knowledge and a diverse set of skills relating to the topics of stoichiometry, bond energy, and kinetics. Parts (a)(i) and (a)(ii) assessed their ability to understand the mole relationships in a chemical reaction. When given quantities of two reactants in part (a)(i), one in grams and one in moles, students were required to mathematically justify their selection of the limiting reactant. In part (a)(ii) students were expected to calculate the amount of product in moles based on their selection of the limiting reactant in part (a)(i). Parts (b) and (c) focused on bond energy; students needed to calculate the energy required to break a bond in part (b) and to calculate the wavelength of electromagnetic radiation required to break the bond in part (c). Parts (d) and (e) required students to answer questions about the kinetics of a reaction. In part (d) they had to recognize the placement and understand the meaning of an intermediate in a reaction mechanism, and in parts (e)(i) and (e)(ii) they were assessed on their ability to determine and justify the order of a reaction with respect to different reactants from the given mechanism.

How well did students perform on this question?

Student performance on this question was generally poor. The mean score was 2.76 out of 8 possible points. The modal score was 2, with roughly 16 percent of the responses failing to earn any points and another 5 percent of the papers left blank. Only about 1 percent of the responses earned all 8 points. Many students earned all the points available for parts (a)(i) and (a)(ii), with the most commonly earned point being the one for part (a)(ii). Another commonly earned point was the one for part (d). Typically, no points were earned for part (e)(i) and especially part (e)(ii); this suggests that the study of mechanisms in kinetics has either been omitted or covered only superficially in the students’ courses.

What were common student errors or omissions?

Part (a)(i)

- Failing to identify the limiting reactant
- Using dimensional analysis incorrectly
- Calculating a numerical answer in moles of reactant or grams of reactant but not showing a relationship or supplying an explanation of the purpose of the calculation
- Miscalculating the molar mass of CH_4
- Using incorrect labels in the setups, an error that showed a lack of understanding of the purpose of the calculations
- Neglecting to pay attention to the given units (e.g., labeling "2.58" as grams instead of moles and then dividing by 70.9 g/mol to get moles)
- Using ICE charts
- Mentioning a reactant that was not involved in the reaction (e.g., O_2)
- Choosing a product as a limiting reactant
- Calculating the excess amount of a reactant

Part (a)(ii)

- Supplying the correct answer with no supporting setup
- Supplying the answer in grams instead of in moles

Part (b)

- Calculating joules per mole when joules per bond was requested
- Using dimensional analysis incorrectly (e.g., multiplying by Avogadro's number)
- Demonstrating an inability to convert kilojoules to joules
- Failing to realize that Cl_2 has only one single bond

Part (c). Many students lost both points for this part, perhaps because they were exposed to the energy and wavelength equations in their first chemistry course and failed to revisit that type of problem in the AP Chemistry course. Common errors included:

- Neglecting to substitute the answer from part (b) into the energy equation
- Making algebraic errors in combining the two equations
- Supplying incorrect answers, even though calculators were permitted
- Ignoring powers of 10 (exponents)
- Using inappropriate equations, such as $E_n = \frac{-2.178 \times 10^{-18}}{n^2}$, $E = mc^2$, and $\lambda = \frac{h}{m\upsilon}$
- Failing to recognize whether an answer is reasonable (e.g., wavelengths of 10^{47} and 10^{-301} meters or negative values of wavelengths)
- Using improper values for the constants h and c

Part (d)

- Failing to fully justify their choice
- Having misconceptions of the role, the placement, and even the presence of catalysts in a mechanism
- Using the argument that since it is not a catalyst it must be an intermediate

Parts (e)(i) and (e)(ii)

- Confusing order with respect to a reactant with overall order
- Failing to relate the order to the rate-determining step
- Supplying the order, sometimes correctly for both parts, without justification
- Confusing rate-law expressions with equilibrium expressions
- Referring vaguely to the molecularity of reactions
- Failing to realize that substances in reactions all have coefficients (even though 1 is an understood coefficient, it is still a coefficient)
- Supplying the order based on the step in which a species appears (e.g., first order because it is in step 1, second order because it is in step 2)
- Using the coefficient–exponent relationship from the overall balanced equation or from a fast step (some students wrote the rate-law expression based on this relationship)
- Justifying CH_4 as being first order because the reaction is slow and then Cl_2 as second order in part (e)(ii) because it is fast
- Stating that two reactants means second order

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?

- Require students to (1) label all parts of their setups and (2) both justify using quantitative methods and verbally explain how a limiting reactant can be identified; doing so might improve their performance on stoichiometry problems.

- Emphasize estimating skills and discuss the reasonableness of numerical answers.

- Revisit first-year or first-semester calculations of energy, frequency, and wavelength by supplying review problems for students to solve.

- Require students to practice writing, interpreting, and deriving rate laws from reaction mechanisms.

- Require students to distinguish between overall order and order with respect to a reactant.

- Require students to suggest possible mechanisms when supplied with an overall balanced equation.

- Require students to discuss molecularity.

- Supply examples from several textbooks and other resources to illustrate that orders with respect to reactants can be fractions as well as whole numbers.

- Demonstrate or supply computer simulations, if available, to aid students in the recognition of catalysts and intermediates.

Question 4

What was the intent of this question?

This question assessed students' ability to communicate their knowledge of chemical processes. Important skills tested included writing chemical formulas for substances and balancing equations. Additional aspects of the problem evaluated general understanding of chemical concepts presented to students in both the classroom and the laboratory.

How well did students perform on this question?

Students displayed a wide range of knowledge and skills in their responses to this question. The mean score was 8.43 out of 15 possible points. The scores covered the entire scale and had a bell-shaped distribution. The most common scores were in the 7–12 range. Approximately 5 percent of the responses earned a score of 15, and there were relatively few blank papers.

What were common student errors or omissions?

Part (b)

- Omitting charges where required (e.g., NH_4 instead of NH_4^+)
- Ignoring the extensive ionization of hydrochloric acid or ammonium chloride (e.g., writing $NH_3 + HCl \rightarrow NH_4Cl$ rather than $NH_3 + H^+ \rightarrow NH_4^+$)
- Treating ammonia as a strong base
- Including spectator ions
- Failing to recognize that NH_4^+ is a weak acid or that it is the conjugate acid of NH_3
- Failing to write the reaction that occurs in solution as prompted (students sometimes just described the reaction between NH_3 and HCl to form NH_4Cl)
- Failing to recognize the hydrolysis of the ammonium ion in the resulting solution, which produces the acidic solution
- Identifying the resulting solution as being "acidic" but then writing that the "pH increased"

Part (c)

- Confusing a decomposition reaction (e.g., $2\ HgO \rightarrow 2\ Hg + O_2$) with an ionic dissociation reaction (e.g., $HgO \rightarrow Hg^{2+} + O^{2-}$)
- Writing the decomposition reaction as a combustion reaction with impossible products (e.g., $HgO + O_2 \rightarrow CO_2 + H_2O$)
- Neglecting to make it clear that decomposition reactions do not result in a decrease in the mass of the system unless a gas is released and allowed to leave the reaction system

All parts

- Showing molecules and uncharged compounds (whether they were solid, liquid, or gaseous) in an ionized form (e.g., Hg^{2+}, NH_3^+, O^{2-}, CO_2^{2-}, Fe^{3+}, and C^{4-})
- Neglecting to balance chemical equations by charge

- Placing oxidation numbers, or other extraneous numbers, within the balanced equation answer box (e.g., $2\ Fe_2^{+3}O_3^{-2} + 3\ C \rightarrow 3\ C^{+4}O_2^{-2} + 4\ Fe$)
- Writing incorrect formulas (e.g., writing FeO_3 or Fe_3O_2 rather than Fe_2O_3, or writing Hg_2O or HgO_2 rather than HgO)
- Writing more than one chemical equation in the answer box
- Writing explanations or justifications that were not consistent with the chemical equation in the answer box

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 practice not only with balancing equations stoichiometrically but also with incorporating charge balance simultaneously.
- Students need to understand the significance of chemical nomenclature when writing chemical formulas for molecules, atoms, and ions in solution. Consider the following equations: $NH_3 + H^+ \rightarrow NH_4^+$ and $NH_3 + HCl \rightarrow NH_4Cl$. The first equation is correct. The second equation is incorrect because it does not indicate that hydrochloric acid and ammonium chloride completely ionize in water.
- Students need to be reminded that the answer box should contain only the final, balanced chemical equation. Emphasize that the box should not contain oxidation numbers, scratch work, any other extraneous charges or numbers, or extra equations.
- Students need to be very familiar with the list of common strong acids and strong bases and know that everything else is a weak acid or base. Many students indicated that NH_3 is a strong base. This misconception led to points lost in part (b)(ii).
- Students need to know the names and symbols of elements commonly used in examples in textbooks. Students substituted Pb for Fe and Ca for C in part (a)(i) and Mg for Hg in part (c)(i).
- Students need to be able to compare and contrast the results of mixing an acid with a base. Utilize general pH curves to support the concepts associated with the acidity/basicity of the resulting solution when mixing weak acid–strong base, strong acid–weak base, and strong acid–strong base systems. The process of *neutralization* (more accurately referred to as "reaching the equivalence point") does not always mean the formation of a *neutral* (pH = 7) solution. It is suggested that the word *neutralization* be used carefully in order to avoid confusion.
- Students need to understand the sequence of events that leads to the formation of the conjugates. In the reaction $NH_3 + H^+ \rightarrow NH_4^+$, rather than observing that NH_3 accepts the proton and is therefore the base, students incorrectly concluded that NH_4^+ is a conjugate base because it was formed by "accepting a proton."

- Students need to realize that the acidity or basicity of any resulting solution is dictated by the conjugate ions in solutions (the focus is on the ions that compose the aqueous salt) and not on the acids or bases mixed together. For example, a resulting solution of $NH_4Cl(aq)$ is acidic due to the hydrolysis of NH_4^+ ($NH_4^+ + H_2O \rightarrow NH_3 + H_3O^+$) and not because a strong acid (HCl) reacted with a weak base (NH_3).

Question 5

What was the intent of this question?

This question assessed students' conceptual understanding of equilibrium, thermodynamics, and kinetics through a series of questions about three related chemical reactions and their corresponding thermodynamic data. In part (a) students were asked to write the pressure equilibrium expression, which tested the ability to distinguish between pressure equilibria and concentration equilibria. In part (b) students were asked to predict and justify the change in the equilibrium constant when the temperature increases, which tested their skill at applying thermodynamic data to a disturbance in the equilibrium system. Part (c) required students to use the thermodynamic data ($\Delta G°$) to predict and justify the magnitude of K_p relative to 1. Part (d) tested their understanding of the approximate relationship of enthalpy to the mathematical difference between energy of bonds being broken and bonds being formed in a chemical reaction.

Part (e) tested conceptual understanding of both thermodynamics and kinetics by asking if there is any relationship between the two. In part (f)(i) students were asked to predict and justify the sign of $\Delta S°$. This tested their understanding of Hess's law, since the reverse of reactions X and Y add up to reaction Z. Students could also have answered this question by demonstrating an understanding of the concept of the change of entropy between the reactants and the products in a chemical reaction. For part (f)(ii) students had to find the actual value of $\Delta H°$, so understanding of Hess's law was vital. Part (f)(iii) required them to predict and explain what would happen to the pressure in a sealed vessel containing the reactant and only one product. Since the system was not at equilibrium, students were expected to predict in which direction the reaction would proceed (not shift) and what effect that process would have on the initial pressure.

How well did students perform on this question?

Students did not perform well on this question. The mean score was only 2.15 out of 8 possible points. A significant number of students addressed all parts of the question but still earned a score of 0. Often, students earned no points because both the prediction *and* the explanation had to be correct to earn the point. Another factor contributing to the difficulty of this question was the number of different concepts that many of the parts included.

Students most frequently were able to answer part (f)(i) correctly, with the second most frequently correct part being (f)(ii), which asked students to find the value of $\Delta H°$. Students brought several types of misunderstandings to each of the other parts of the question, resulting in low scores. Many times the difference between a score of 7 and a score of 8 was an incorrect answer to part (d).

What were common student errors or omissions?

Part (a). This part was most frequently incorrect. Common errors included:

- Writing the expression for K_c instead of K_p (the most common mistake by far)
- Writing $K_p = K_c(RT)^{\Delta n}$ as the sole expression for K_p , not specifying the equilibrium expression for K_c , and/or not specifying the value for Δn
- Including the pressure of solid C in the K_p expression
- Writing $K_p = \dfrac{[CO_p][H_{2\,p}]}{[H_2O]}$

Part (b). Roughly half the students answered this part correctly by using the positive enthalpy value and Le Chatelier's principle as justification for an increase in K_p . Common errors included:

- Explaining the increase in K_p as being due to an increase in the pressure of the reacting species as a direct result of the increase in temperature
- Explaining the increase in K_p as the result of a temperature increase, implying that all equilibria shift to the right as the temperature of the system increases (thus omitting the dependence on $\Delta H°$)
- Failing to recognize that a positive $\Delta H°$ signifies an endothermic reaction
- Substituting temperature in the equation $K_p = K_c(RT)^{\Delta n}$ and concluding that K_p increased, without considering the effect on K_c
- Using the argument that if entropy is positive, an increase in temperature would result in an increase in $\Delta G°$, which results in a K_p less than 1 ($\Delta G° = \Delta H^{\circ}_{298} - T\Delta S^{\circ}_{298}$ and $\Delta G° = -RT \ln K_p$); this argument fails to recognize that $\Delta G°$ itself is strongly dependent on temperature

Part (c). Many students were able to earn the point for this question. The most common errors were:

- Equating K_p to 1 by looking at the expression for K_p for this reaction
- Substituting equal pressures (or concentrations) for all species

Part (d). The majority of students did not earn the point for this part. Common errors included:

- Stating that an endothermic reaction (or positive $\Delta G°$ and/or $\Delta S°$) results in a greater bond energy for the products (this was the most common incorrect answer)
- Identifying *some* of the bonds (e.g., double bonds in CO_2) as being more difficult to break than others
- Stating that the bond energy of the reactants is greater because it is an endothermic reaction and therefore the reaction needs energy to break the reactant bonds
- Justifying that the total bond energy of the reactants is greater because the reaction is endothermic but not *explaining* that the enthalpy is a result of the energy difference between bonds being broken and bonds being formed

- Assuming that the total bond energy of the products is greater based on the equation

$$\Delta H^\circ = \sum \Delta H^\circ_{f(products)} - \sum \Delta H^\circ_{f(reactants)}$$

Part (e). The majority of students did not earn the point for this part. The most common error was:

- Using any or all of the thermodynamic data in the table to explain either a true or false answer

Part (f)(i). The majority of students earned this point. If a student earned any points on question 5, this part of the question was typically the one that was correct. Common errors in this part included:

- Explaining the negative entropy change by writing a definition of a change in entropy with no reference to the specific reaction
- Using the argument for a Hess's law relationship but failing to specify that both reactions need to be reversed
- Equating entropy change to 0 because of the equal number of moles of reactants and products
- Explaining the change in entropy with generic references to "it" and without an identification of physical state of matter
- Stating that because a solid was formed there was a reduction in entropy

Part (f)(ii). This was the question's second-highest-scoring part. Students who realized how to do this made very few mistakes. Common errors included:

- Neglecting to reverse the second reaction and to change the sign on the corresponding enthalpy change
- Answering the question as a positive or negative enthalpy change but not giving a specific numerical value
- Making mathematical errors with no support for the answer

Part (f)(iii). This was another low-scoring part. Common errors included:

- Using the relationship of pressure, temperature, and volume (with no regard for reaction Z) to conclude that the pressure remains the same
- Explaining that the pressure remains the same because no reaction will take place between CO(*g*) and C(*s*)
- Explaining that pressure decreases because CO is decomposing, without relating a change in pressure to fewer moles of gas
- Explaining that pressure will increase because CO is forming
- Using Le Chatelier's principle to describe what will happen in a system that is not initially at equilibrium
- Explaining that there was no change in pressure because the moles reacted equal the moles formed
- Neglecting to explain the pressure decrease in terms of number of moles of gas changing
- Explaining that pressure will decrease because a solid is formed

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?

- Give students the opportunity to respond to essay questions and evaluate them with the AP Scoring Guidelines. Many students answered the questions with a definition of terms and without regard to the specific question or reaction, a practice that does not earn points.
- Stress that students' answers to essay questions need to be expressed in clear and concise language. This takes skill, practice, and a good understanding of the concepts.
- Give students practice with approximating answers to mathematical equations by manipulating variables and using approximate values (this will help them with the multiple-choice section as well).
- Stress the need to understand the chemistry behind any mathematical relationship that is being employed. Students used equations that were given in the exam booklet without understanding the conceptual relationships.
- Take advantage of the fact that many concepts may be tested in a single problem. This question covered concepts of equilibrium, thermodynamics, and kinetics. Provide students with similar questions so they can practice switching from one topic to another or integrating topics.
- Emphasize that the parts of a question are often not dependent on each other. Students should read through the entire question; if they cannot answer one part, they may be able to answer a subsequent part.
- Stress that it is absolutely necessary to read a question closely to determine any conditions that may be variable or constant. The impact on the answer is obvious.
- Emphasize, as usual, that units are important.

Specific suggestions for teachers to follow when teaching the AP Chemistry course include:

- Stress the differences in all the K_{eq} possibilities and the corresponding expressions.
- Continue to stress what each of the thermodynamic quantities means both qualitatively and quantitatively, as well as the conclusions that can be drawn from each of these. Students seemed to have a clear understanding of entropy change and how to apply this concept to a chemical reaction; however, they had a difficult time applying the concepts involving changes in both enthalpy and Gibbs free energy. Students may have understood the mathematical relationships, but answering a question without doing the math was difficult for them.
- Help students to understand bond energy and the relationship with enthalpy. Responses clearly demonstrated that many students did not understand that energy is needed to break reactant bonds and that energy is released when product bonds are formed.
- Help students understand when and how to use Le Chatelier's principle. If the system is not at equilibrium, Le Chatelier's principle cannot be applied. Students had a difficult time answering a question correctly when given the initial conditions of a reaction before equilibrium had been established.

- Continue to stress, when presenting the equilibrium unit, that spontaneity does not imply a rate for the reaction. Many students knew that rate data need to be experimentally found, but when presented with thermodynamic data they tried to answer the question using the given information.
- Work more with reactions and gas laws. Many students used the ideal gas law when presented with a question about pressure and totally disregarded the fact that a reaction might be taking place.
- Stress the fact that when two substances are put together they do not have to react with each other.

Question 6

What was the intent of this question?

This question tested students' ability to use principles of atomic structure to predict atomic properties and to explain molecular properties. In part (a) students had to complete the electron configurations for S and S^{2-} and then use these configurations to predict and explain two property differences. In part (b) students had to predict and explain another atomic property difference for S^{2-} and Ar. In part (c) they had to use the observed bond angle in H_2S to identify the orbitals of the S atom that are involved in bonding to the H atoms. In part (d) students had to compare the relative strength of the London dispersion forces and dipole–dipole attractions of H_2S and H_2O.

How well did students perform on this question?

Student performance on this question was relatively good. The mean score was 3.52 out of 8 possible points. In general, students showed a good understanding of both atomic structure and observed properties, but they often had some difficulty interrelating these.

In part (a) most students were able to complete the electron configurations for S and S^{2-}. In part (c) many students were able to correctly identify the 3*p* orbitals of S as those involved in bonding with H atoms in H_2S, based on the bond angle being close to 90°. Students did fairly well on part (d): there was less confusion between covalent bond strength and the strength of intermolecular forces than had been seen in previous years.

What were common student errors or omissions?

Part (a)

- In explaining why the radius of S^{2-} is larger than that of S, most could indicate that S^{2-} had the greater number of electrons, but they could not also indicate that this would increase the magnitude of the electron–electron repulsions.
- Many students failed to identify the unpaired electrons as being the cause of paramagnetism of S atoms; instead, they erroneously indicated that a charge is attracted into a magnetic field or that a magnetic pole has a charge.

Part (b)

- Most students predicted that it is easier to remove an electron from S^{2-} than from Ar. Many students had difficulty, however, identifying nuclear charge as being responsible for this.
- Electron configuration, location in the periodic table, and total charge were inappropriately referenced factors.

Part (d)

- Many students could identify the substance with the stronger of both types of intermolecular forces, but there was a broad range of difficulties with the explanations.
- Some students compared the relative strength of London dispersion forces and dipole–dipole forces for one molecule, instead of comparing two molecules for one type of intermolecular force.

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?

It is evident that students have been exposed to the material covered by this question. Students understood atomic structure: numbers of electrons and protons and electron configurations. They also seemed to know the factors that determine atomic and molecular properties, charge attractions, and charge repulsions. Some areas, however, are in need of improvement:

- Choosing which structure factor predicts and explains a particular property trend remains a problem for many students.
- Students need to better understand paramagnetism, particularly that it is *not* the result of an electrostatic attraction.
- Students need to understand that reference to a periodic table trend does not constitute an explanation and that mass is not an explanation for trends in the strength of London dispersion forces.