CollegeBoard
Advanced Placement Program

Student Performance Q&A:

2007 AP® Chemistry Free-Response Questions

The following comments on the 2007 free-response questions for AP® Chemistry were written 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 students' understanding of aqueous equilibrium of a weak acid, stoichiometry of aqueous reactions, and buffer calculations. For parts (a) and (b) students were given a chemical equation describing the equilibrium of a weak acid in aqueous solution; they were expected to write a correct expression for the equilibrium constant and to use the equilibrium-constant expression and its value to determine $[H_3O^+]$ in a solution of known concentration. The remainder of the problem challenged students first to perform stoichiometric calculations to determine the number of moles or the concentration of species present when solutions of a weak acid and a strong base are combined. The final part of the question asked them to demonstrate mastery of the concept of buffered solutions by determining the pH of the resulting solution.

How well did students perform on this question?

Students did a good job answering this question, earning a mean score of 4.48 out of a possible 9 points. The distribution of scores was quite uneven, possibly due to interdependence among parts of the question, but the large percentage of scores of 8 and 9 indicated that many of the students had mastered the concepts. Even with the peaks and valleys of the score distribution, there was little clustering of scores and the entire range was utilized.

Students were generally successful on parts (a) and (b), and responses that earned 1 to 3 points usually garnered them here. Parts (c), (d), and (e) offered more challenges. Students who were able to shift gears and recognize that parts (c) and (d) were fundamental stoichiometry problems were quite successful; however, many students continued to apply equilibrium concepts and equations to these parts and

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consequently did not earn most of the available points. Similarly, students who recognized the solution as a buffer were generally able to earn at least 1 point, and often 2 points, on part (e); however, this was a minority of the exam-takers.

What were common student errors or omissions?

Part (a): This part was most frequently correct, and students who earned 1 point usually wrote a correct equilibrium-constant expression. Common errors included omitting charges in the equilibrium-constant expression and including the solvent in the equilibrium-constant expression.

Part (b): This part was also answered correctly quite frequently. Common errors included failing to recognize that $[H_3O^+]_{eq} = [F^-]_{eq}$ in this solution, incorrectly assuming that $[F^-] = [HF]$, or substituting an incorrect value for the initial $[F^-]$. Many students did not make the justified approximation that $\Delta[HF] << \text{initial } [HF]$, and a number of them tried unsuccessfully to solve a quadratic equation (frequently using the quadratic formula!). Many students failed to round the final answer appropriately.

Parts (c) and (d): Four points were available for parts (c) and (d), and these parts were tied together. Many students combined their work on these parts of the question. Common errors included incorrectly attempting to apply principles of equilibrium and equilibrium calculations, and failing to understand the distinctions among the amount of substance initially present, the amount that reacts, and the amount that remains. Many students did not answer the questions that had been asked; they often gave a concentration rather than the number of moles of HF in part (c), or the number of moles of F^- rather than the concentration in part (d). Many students did not make the distinction between L and mL, and some made simple arithmetic errors (e.g., 25 mL + 15 mL = 35 mL).

Part (e): This was the most challenging part for students to answer correctly. A common error was failing to recognize that *both* a weak acid and its conjugate base are present in the solution. Students also had trouble determining the pH of a weak acid *or* a weak base. Many students treated the solution as either a strong acid or a strong base and attempted to calculate the pH as the $-\log_{10}$ of the concentration of some species present. Many students substituted incorrect concentrations into the equilibrium-constant expression or the Henderson-Hasselbalch equation.

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?

- Continue to stress fundamental stoichiometry and the distinctions among *initial* amounts (or concentrations), *reacting* amounts, and *final* or *equilibrium* amounts.
- Be sure to address the distinctions among number of moles, volume, and concentration, and the relationships among them; students need to understand which one is asked for in the question.
- Work to ensure that students can recognize the qualitative aspects of a problem before attempting to apply equations.
- Deemphasize overly complex numerical calculations. Students are often unable to solve quadratic equations correctly in a test setting, and justifiable approximations will generally obviate the need to solve quadratic equations on the examination.

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Question 2

What was the intent of this question?

The intent of this question was to measure students' understanding of thermodynamics for a particular reaction. Students were asked to calculate ΔG°_{298} using the thermodynamic data provided to predict the temperature at which the reaction is at equilibrium, to calculate the enthalpy for a specific number of moles of product, and to relate the number of bonds broken and formed to the bond energies and the reaction enthalpy in order to calculate the average enthalpy of the F–F bond.

How well did students perform on this question?

This question produced a full range of scores, with a mean score of 3.93 out of a possible 10 points. Very few students left this question blank; they seemed willing to attempt to answer one or two parts, leading to the most common scores of 1 or 2. Students were generally able to recognize that Gibbs free energy is a function of enthalpy, temperature, and entropy when used in an equation; however, for the most part they did not understand conceptually that ΔG is temperature dependent. And even though most students were able to determine the number of bonds in the product for this reaction, there seemed to be little correlation between bond energy calculation in part (e) and the number of bonds identified in part (d).

What were common student errors or omissions?

Part (a): The vast majority of students were able to correctly insert enthalpy, temperature, and entropy into the correct locations of the equation to calculate ΔG°_{298} . Beyond that, unit conversion errors, calculation errors, significant figure errors, and unit labeling errors prevented students from earning another point. Although the unit conversion error seems consistent with past performance on thermodynamics questions, significant figure errors and answers without units seemed to occur more often.

Part (b): This was the most challenging part of the question and therefore the least attempted and the lowest-scoring part. When students did attempt this part, they chose one of two possible paths to solve the problem. By recognizing that ΔG°_{298} is zero when $K_{eq} = 1$, some students were able to complete the calculation and find the temperature at which the equilibrium is established (barring any of the errors described in part [a]). However, the majority of students used the equation $\Delta G^\circ_{298} = -RT \ln K_{eq}$, presumably because it had all the variables needed to solve the problem. Not recognizing that ΔG is temperature dependent, students substituted the value produced in part (a), ΔG°_{298} at 298 K, in part (b). Resolving this mathematical impossibility was difficult for the students. Many of the responses ignored the fact that ln(1) is zero and calculated a temperature based on the other information. Many came to the conclusion that temperature could be any value since any value times zero is still zero. The remaining students stated that it was impossible to calculate a temperature because dividing by zero is undefined.

Part (c): Slightly more than half of the students attempted this part. Most were able to answer at least some of it correctly, while others tried to use the ideal gas law (since a temperature and pressure were given). Of the students who calculated the answer by multiplying the number of moles of NF_3 by an

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enthalpy value, about two-thirds recognized the stoichiometry of the equation and interpreted the given ΔH° as being for the reaction as written. However, only a handful of students out of the 93,000 responses used the interpretation of the enthalpy per mole of NF_3 in every applicable part of the question.

Part (d): Most students were able to determine the correct number of bonds produced in this reaction as written. Since the highest percentage of students received a score of 1 or 2 on the question, this part contributed to the majority of scores of 1 and together with part (a) resulted in the mode score of 2. For many students, however, this was the only part addressed in the question. Some students drew structures of the 2 NF_3 as a single molecule with various configurations of single, double, and triple bonds. The number of bonds varied correspondingly.

Part (e): There were several situations in which students did not earn full credit in part (e). The most notable trend observed in this part was the lack of correlation between the answer in part (d) and the substitution of number of bonds in the equation. If a student stated the correct number of bonds for part (d), another number (such as 2) would sometimes appear in part (e) as the number of bonds in 2 NF_3 molecules. If a student wrote an incorrect answer in part (d), the correct number of bonds would sometimes be substituted in part (e). This latter answer earned 1 point even though there was no consistency or perhaps no understanding of the connection. Another common error was to calculate the bond energy of F_2 by using a "products minus reactants" equation for determining enthalpy. The last common error for part (e) was the misconception that the bonds broken equal the bonds formed, with students neglecting to consider the role of the reaction enthalpy.

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 stress the following with their students:

Math/Measurement Skills:

- the necessity of significant figures and attention to units, both within an equation and in the answer
- algebraic and arithmetic manipulations in obtaining an answer
- the importance of checking the reasonableness of an answer (e.g., negative Kelvin temperatures or negative bond energies)

Chemical Concepts:

- Connecting the concepts of thermochemistry with molecular structures—perhaps an activity using molecular modeling, not only for individual molecules but also for entire reactions, would help with this topic. It does appear, however, that students are getting better at relating bond energies to the reaction enthalpy.
- The relationship of Gibbs free energy to temperature—the real issue to address may be the problem of obtaining an unreasonable answer. Brainstorming strategies needed to resolve that dilemma could be beneficial.

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Question 3

What was the intent of this question?

This question analyzed an electrolysis experiment. It evaluated students' skills in a number of areas, including electrochemistry, stoichiometry, thermodynamics, and gas laws.

How well did students perform on this question?

The mean score for this question was 3.70 out of a possible 10 points. There was a wide, descending distribution of scores, with about 5 percent of the students scoring a perfect 10.

What were common student errors or omissions?

Part (a): The direction of electron flow was frequently reversed.

Part (b): The chemical equation was sometimes reversed or not balanced.

Part (c): The sign given for $\Delta G°$ was often incorrect. Many students gave the correct sign but did not give an explanation.

Part (d): Common errors included using incorrect n values, calculating $E°$ incorrectly (e.g., adding the two positive $E°$'s given, doubling the +0.34), and expressing the answer with incorrect units or too many significant figures.

Part (e): Many students calculated the amount of charge transferred correctly but then could not convert this into the number of moles and mass of Cu.

Part (f): Many students could not correctly convert the amount of Cu (or electrons) into moles of O_2. Some students calculated the volume of an assumed one or two moles of O_2 and did not relate the result to the data from parts (e) and (f).

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 be able to use a table of electrode potentials to determine the standard cell potential and the balanced overall equation for an electrochemical cell.
- Students need to focus on which half-reaction gets reversed.
- All aspects of quantitative electrochemistry, stoichiometry, and thermodynamics should be reviewed.
- Students need to practice with multistep calculations, especially calculations involving the integration of formulas and concepts from more than one topic.

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Question 4

What was the intent of this question?

This question assessed students' understanding of precipitation reactions, gas-forming reactions, and oxidation-reduction reactions. Key points covered were:

- application of solubility rules to reactants and products in a reaction
- knowledge of spectator ions and how to handle them
- writing correct net-ionic equations
- application of solution stoichiometry for a reaction-limiting reagent
- knowledge of mass and charge balance
- knowledge of nomenclature

How well did students perform on this question?

The average score for this question was 7.63 out of a possible 15 points. Many students scored 2 of the 4 reaction points in part (a). Fewer points were earned in part (b) than in the other two parts of the question. One of the most common points earned was for the explanation for the question about statue deterioration in urban areas. Students are generally aware of industrial gases resulting in the formation of acid rain and the acid rain reacting with the marble. Many students earned 1 of the 5 points in part (b) for this. The most commonly earned points in the question were for part (c); many responses earned 5 out of 5 points. Students who did not write the reactants correctly could still earn points for a silver species being reduced and an iron species being oxidized.

What were common student errors or omissions?

Part (a)(i): Many students did not know correct symbols, formulas, or charges (e.g., the formula or the charge of the nitrate ion), and many did not know that NaOH and $Pb(NO_3)_2$ are soluble. Many students wrote the reactants as molecules and thus did not write the net-ionic equation for the reaction. If the product was correct and the equation written was balanced, this often earned 2 of the 4 reaction points. Charges with species should be reserved for ions in a balanced chemical equation, whether it is a net-ionic equation or the complete molecular equation, but some students randomly wrote charges by formulas. If charges were not balanced, no balancing point was earned.

Part (a)(ii): Many students could not determine which reactant was the limiting reactant. Many students used the reaction coefficients for this answer, which gave an answer of 3 moles of products being formed. Some students included the number of moles of ionic species as products formed. Other students wrote "*M*" for mole, which did not earn them the point.

Part (b)(i): Nomenclature played a key role in the scores for this question. Many students did not know the formula of nitric acid; in general, if the formula did not contain the elements N, H, and O, no reaction points were earned. Also, many students did not write nitric acid as a strong acid that dissociates completely into ions. Many students did not read the question carefully and did not write $CaCO_3$ as a solid. They did not need to know whether or not $CaCO_3$ was soluble because it was given as a solid. A common error was to stop at the formation of H_2CO_3 or HCO_3^- and not carry the reaction out to completion: in excess nitric acid, the carbonic acid reacts to form CO_2 and H_2O. Writing the balanced

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molecular equation with products H_2CO_3 and $Ca(NO_3)_2$ was common; this earned the balance point in part (i). Many students did not know the formula of the carbonate ion or that $Ca(NO_3)_2$ is soluble.

Part (b)(ii): Students generally did well on this part.

Part (c)(i): A common error was to use Fe(*s*) rather than Fe^{2+} as a reactant. Students who had Ag^+ acting as an oxidizing agent and Fe acting as a reducing agent earned the product points. If that equation had mass and charge balance, they also earned the balance point. Some students did not know what oxidizing agents and reducing agents are. Some students gave Au as the symbol for silver and Pb as the symbol for iron.

Part (c)(ii): Many students were able to look at their written products and determine the solid that would remain on the filter paper. Some students did not grasp that species in solution passed through the filter paper and solids remained on the filter paper.

General errors included:

- treating all reactions as double-replacement reactions
- writing charges over compounds that are not ions
- leaving spectator ions on both sides of the equation
- adding e^- to one side of the equation to balance the charge

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?

Teach your students:

- symbols for the elements
- nomenclature of atoms and ions
- charges on ions
- how to correctly write formulas for compounds that contain polyatomic ions
- to memorize the strong acids and bases
- gas-forming reactions
- mass and charge balance for all reactions
- net-ionic equations (spectator ions)
- to differentiate between types of reactions (e.g., nitric acid is not always an oxidizing reagent)
- the symbols for molarity (*M*) and mole (mol)
- to determine the kind of a reaction before writing the products
- how to determine the limiting reagent
- how to use the supplied reduction table to determine the changes in oxidation numbers
- what (I) and (II) associated with metal ions signify

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Question 5

What was the intent of this question?

The purpose of the laboratory question was twofold: to evaluate students' knowledge and laboratory experience in performing a redox titration, and to assess their ability to communicate conceptually using data collected in the laboratory. In parts (a) and (b) students were asked to identify the oxidation number of Mn in MnO_4^- and also to identify the reducing agent in the given reaction. Part (c) required them to identify the color change in the flask at the endpoint of the titration and the reason for the color change. Part (d) asked students to use assigned variables to provide the mathematical expressions necessary to calculate the percentage of iron in an unknown sample. Part (e) was an error analysis component in which students were asked to predict the effect of adding too much titrant and had to justify their answers.

How well did students perform on this question?

This question produced a full range of responses. The mean score was 3.21 out of a possible 9 points. Many students earned a total score of 2 for having correct answers only in parts (a) and (b). Students demonstrated average performance in part (d); assigning variables with no units occasionally led to erroneous calculations and misinterpretations. In part (e) many students correctly answered the question linking the effect of adding too much titrant to the expression given in part (d)(iii).

What were common student errors or omissions?

Part (a): Most students identified the correct oxidation number.

Part (b): The most common error was not identifying Fe^{2+} as the reducing agent. Many students stated that "iron" was the reducing agent or wrote the expression "$Fe^{2+} \rightarrow Fe^{3+}$"; these students did not earn the point.

Part (c): The students who had not performed this common redox titration had difficulty with this part of the question. Many students confused the terms *endpoint* and *equivalence point*, and they confused this titration with an acid-base titration and the indicators used in an acid-base titration. Although many students knew that MnO_4^- is purple, they gave no indication of its usefulness in the titration as its own indicator when it is in excess. Many students received the first point for the color change but did not earn the second point for the explanation.

Part (d): In part (i) the most common error was dividing some number of grams by molar mass to obtain moles. In part (ii) many students correctly used the answer in part (i) and received a consistency point for multiplying by molar mass. In part (iii) many students did not use the stated variable g as the denominator in the expression and instead listed all of the components in the solution. Many students wrote the quotient without supplying the multiplier of 100; these students did not earn one of the points.

Part (e): The most common error in this part was the idea that adding too much titrant would cause the percentage of iron to decrease because the mass of the solution increases. Many students did not describe the effect with the terms *increase* or *decrease*, and many did not justify their answers.

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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 make certain that their students:

- perform hands-on laboratories (all of the recommended experiments) and are given time for collaborative discussion and analysis of results
- have a variety of opportunities to write and understand mathematical expressions from laboratory data
- recognize that a variety of errors implicit in every measurement made in the laboratory will have an effect on final calculated answers—and be able to describe that effect
- distinguish clearly between endpoint and equivalence point with specific examples from the laboratory (not just by definition)
- use common laboratory terminology, such as *titrant*, when completing laboratory reports
- distinguish between different types of percent: percent of a component, percent error, percent yield
- are held accountable for work performed in the laboratory by completing lab-related questions on a variety of assessments

Question 6

What was the intent of this question?

Parts (a) through (d) of this question probed students' understanding of bonding models for simple binary compounds. Students needed to be familiar with Lewis electron-dot diagrams, the valence shell electron pair repulsion model, and valence bond theory (hybridization). Parts (e), (f), and (g) measured students' understanding of the factors that affect chemical reactions and required them to combine thermodynamic and kinetic factors in their arguments.

How well did students perform on this question?

The mean score was 3.60 out of a possible 9 points. The most commonly missed part was part (g).

What were common student errors or omissions?

Part (a): Miscounting the electrons and omitting the electrons on the fluorine atoms were the most commonly seen errors in this part.

Part (b): The most common error here was giving the *electronic* geometry (trigonal bipyramidal). Students who ignored the lone pairs in their Lewis diagram or put the lone pairs on the axial sites gave triangular planar as the structure. Other common incorrect answers were "seesaw," "tetrahedral," and "trigonal pyramid."

Part (c): Miscounting valence electrons (18 were needed) and drawing structures with incomplete (or expanded) octets were the most common errors in writing the Lewis diagrams. A major misunderstanding surfaced concerning the interpretation of the term *resonance*. Students incorrectly wrote of electrons (or bonds) "oscillating between the oxygens," "flopping back and forth," "switching back and forth," or "rotating around the molecule," rather than using the delocalized picture that is more consistent with

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reality. A surprisingly common error centered around an argument that the S–O bonds were of equal length because the lone pair on the sulfur atom repelled (or attracted) the oxygen atoms equally. Arguments about bond length or strength must be based on the number of bonding electrons, not on properties of lone pairs.

Part (d): A significant minority of the students did not recognize what was meant by the term *hybridization of the S atom*. Some confused hybridization with atomic structure, writing that the hybridization of the S atom was "$1s^2\ 2s^2\ 2p^6$…," and some confused a statement of the geometry (*linear* or *bent*) with the corresponding hybridization (*sp* or sp^2).

Part (e): Common errors on the potential energy diagrams included not being able to distinguish between the representation of an *exothermic* and an *endothermic* reaction, not realizing that the starting and ending potential energies for the catalyzed and uncatalyzed reaction paths are the same, incorrectly identifying (or neglecting to identify) which of the two paths represented the catalyzed reaction, and not recognizing that the activation energy for a catalyzed reaction is lower than the activation energy for an uncatalyzed reaction.

Part (f): The most common error in part (f) was the failure to recognize that the key to this question lay in the statement "the reaction is exothermic." Many incorrect arguments were based on temperature-induced pressure changes (ideal gas law arguments), on shifts toward the side with the lower (or greater) entropy (based on the number of moles of gas), or on the belief that the increased kinetic energy of the particles at the higher temperature would shift the reaction equilibrium toward the product side.

Part (g): The major problem with this part was that most of the students did not *carefully* read the question. The question asked them to comment on how a catalyst would affect the shift from one equilibrium position to another equilibrium position, as described in part (f). Few students addressed this question; instead, most discussed how a catalyst would affect the rate of a reaction, starting from some undefined initial conditions, as it went to equilibrium.

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 *clearly* represent the correct number of electrons in a Lewis diagram with easy-to-discern dots or dashes (to represent electron pairs).

- Students should appreciate the difference between molecular structure and electronic structure. The "T-shaped" molecular geometry of IF_3 is based on an electronic structure that is a trigonal bipyramid; the molecular structure (or geometry) depends on the electronic structure (or geometry), but the two terms represent different things.

- Students should come to appreciate the difference between the ↔ and the ⇆ symbols used by chemists. The double-headed resonance arrow (↔) implies that neither individual Lewis diagram is correct but that the actual structure is between the two presented structures. The double-headed arrow does not represent a dynamic process, with bonds rapidly oscillating between two positions, as the ⇆ symbol implies.

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- When asked to predict how temperature would affect a system at equilibrium, students must recognize that they need to find the sign of $\Delta H°$ (or ΔH). Those students who recognized that answering part (f) required honing in on the statement that the reaction is exothermic (given in the stem) almost always answered the question correctly; those who did not recognize the importance of that statement wandered around talking about entropy or pressure changes and were not successful.

- It is impossible to overemphasize that *students must carefully read the question and then answer the question that has been asked.* No extra credit is earned for elaborations, however accurate they may be, that do not answer the precise question asked. Without a specific answer to the specific question, it is impossible to earn credit. Rather than answering the question that had been asked, however, many students answered the question "What is the effect of a catalyst on a chemical reaction?" It was as if these students had seen this straightforward question about catalysts so many times that a preprogrammed answer came out as soon as they saw a question about catalysts on the AP Exam. Teachers should ask their students about important material in different ways, so that a pat answer to a predictable question does not get firmly entrenched.

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