CollegeBoard
Advanced Placement Program

Student Performance Q&A:

2004 AP® Chemistry Free-Response Questions

The following comments on the 2004 free-response questions for AP® Chemistry were written by the Chief Reader, John Gelder of Oklahoma State University in Stillwater, Oklahoma. 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 was designed to test students' understanding of stoichiometry and solution equilibria. Students were asked first to set up a K_{sp} expression from a balanced chemical equation and then to write a balanced equation for dissolving a different salt given the K_{sp} expression. Students needed to make mathematical calculations of a K_{sp} based upon the stoichiometry of the chemical equation and to predict the consequence of disturbing an equilibrium using Q vs. K_{sp} or LeChâtelier's Principle.

How well did students perform on this question?

This was a required question. The mean score was 4.7 out of a possible 10 points. Some students did very well when calculations were required in Parts (b) and (f) but had difficulty explaining concepts clearly in Parts (d) and (g).

What were common student errors or omissions?

Part (a): The most common mistake was the inclusion of $[Ag_2CrO_4]$ as part of the K_{sp} expression. The question asked for the equilibrium constant expression, and many students remembered [products]/[reactants] but did not consider that Ag_2CrO_4 is a solid in the chemical reaction. The second most common mistake was using incorrect charges (or no charges) on the silver and chromate ions, even though they are given in the question.

Part (b): The stoichiometry between the Ag^+ and the CrO_4^{2-} caused the most trouble here. Students routinely assigned the value x to both the $[Ag^+]$ and the $[CrO_4^{2-}]$ and substituted as $K_{sp} = (x)^2(x)$. Even after solving using $x = [Ag^+] = [CrO_4^{2-}]$, they would often attempt to go one additional step with their calculation (e.g., $[Ag^+] = x^2$ or $[Ag^+] = 2x$), and so they would lose the one point already earned for their (incorrect) substitution. The second most common error resulted from incorrect arithmetic, usually $[2x]^2 = 2x^2$. Another common error for students getting the correct stoichiometry and solving correctly was to record the $[CrO_4^{2-}]$, not the $[Ag^+]$, as their final answer.

Part (c): For many students, this part was the most straightforward. Any reasonable value for $[Ag^+]$ or $[CrO_4^{2-}]$ was an acceptable starting point. However, if it was clear that the student was starting with $[Ag^+]$, then the mole ratio of Ag^+ to Ag_2CrO_4 was necessary.

Part (d): Very few students chose to address this question in terms of $Q > K_{sp}$ after the addition of the $AgNO_3$. Instead, almost all attempted to provide a rationale based on LeChâtelier's Principle. This was accepted if they provided some brief discussion—the equilibrium was moved to the left toward solid Ag_2CrO_4, thus reducing the $[CrO_4^{2-}]$ as it reacted with the excess $[Ag^+]$.

Part (e): Most students earned credit for this part. The more common errors resulted from not including correct charges on the ions or including H_2O on the reactant side without in some way acknowledging its presence on the product side.

Part (f): A reasonably large number of students earned full credit for this part. The most common mistake was using the given $[Ag^+] = 5.3 \times 10^{-5}\ M$ as the $[PO_4^{3-}]$. This error resulted in a loss of one point. Other common mistakes included $[PO_4^{3-}] = \sqrt[3]{5.3 \times 10^{-5}}$ or $[PO_4^{3-}] = 5.3 \times 10^{-5}\ M$, so $[Ag^+] = 3 \times (5.3 \times 10^{-5}\ M)$.

Part (g): Most students treated this part as an example of $M_1V_1 = M_2V_2$ and doubled the $[Ag^+]$. There were many papers on which this was the only point missed. In order to earn credit, the student was required to state that the concentration remained unchanged and relate this to some property of a saturated solution.

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?

- Emphasize that equilibrium expressions do not include solids, and that these expressions need to include charges on ions.
- Continue to practice proper algebraic methods (e.g., $[2x]^2 \neq 2x^2$).
- Students need to be able to apply the stoichiometry of a reaction in solving problems and do so consistently.
- Students should have some knowledge of solubility rules.
- Students need to realize that adding a soluble salt with a common ion does affect the concentration of a species in an equilibrium reaction.
- Water does not appear in a solubility-constant expression.
- Students need to understand why removing water from a saturated solution has no effect on the concentration of the dissolved ions.

- Continue to teach balancing equations, and emphasize that an ion's charge is an integral part of its formula and ion charges need to be kept on ionic species in an aqueous solution.
- Emphasize to students that it is to their benefit to write clearly.
- Continue to stress proper explanations with students in class. Discourage students from the use of ambiguous pronouns; often the Reader cannot identify the referent of the pronoun "it". Emphasize that points are earned only when Readers can clearly understand what is written down.
- Provide practice in writing justifications. Emphasize that one-word answers are not considered justifications and that your students need to complete their thoughts.
- Remind students to answer the entire question. Many times a correct relationship did not earn points because the justification was missing.

Question 2

What was the intent of this question?

This question tested the students' knowledge of stoichiometry and thermochemistry and required students to make calculations and provide explanations. The question included mole calculations for a solid and a gas at non-ideal conditions, limiting reactants, and theoretical yield.

How well did students perform on this question?

This question was the much more popular choice, picked by 93 percent of the students. The mean score was 5.2 out of a possible 10 points. Students tended to earn points in Parts (a)(i), (b), (c), and (d)(i) more often than in Parts (a)(ii), (d)(ii) and (e).

What were common student errors or omissions?

Part (a)(i): Few students made errors in this part. Common errors included 1) inversion of grams/atomic mass, 2) the use of incorrect atomic mass, 3) the use of ideal gas equation to calculate moles of Fe(*s*), and 4) simply using the coefficient in the balanced chemical equation.

Part (a)(ii): Errors included 1) the use of 22.4 L for molar volume and then determining moles at ideal conditions and 2) assuming that 11.5 L was 11.5g , or 3) incorrect solving for n in the equation $PV = nRT$ (e.g., $n = RT/PV$).

Part (b): Students often failed to earn points by 1) ignoring stoichiometric ratios of Fe to O_2 when determining the limiting reactant, or 2) incorrect recalling of mechanical "tricks" for determining limiting reactant, or 3) making direct comparison of calculated mole values rather than the stoichiometric ratios (e.g., "O_2 is the limiting reactant because it has the smaller number of moles").

Part (c): Frequently seen errors included 1) misunderstanding of the meaning of the term "limiting reactant" (i.e., having determined the limiting reagent in Part (b) and then using the other reactant for this calculation) and 2) determining grams and not moles of the Fe_2O_3.

Part (d)(i): Common errors included 1) incorrect math for the calculation of the molar entropy calculation 2) incorrect units for the answer, and 3) writing $\Delta G = \Delta H - \Delta S$ instead of $\Delta G = \Delta H - T\Delta S$.

Part (d)(ii): Students often failed to earn points by 1) stating that enthalpy is negative and not mentioning the entropy term, or 2) not making a comparative argument for the relationship between the values of entropy and enthalpy for the reaction, or 3) simply stating the conditions when reactions are spontaneous with no reference to the problem

Part (e): Errors commonly made included 1) using the reverse reaction $Fe_2O_3(s) \rightarrow 2\ FeO(s) + \frac{1}{2}\ O_2(g)$ as the formation reaction for $FeO(s)$ and then taking one half of 280 kJ for the answer and 2) ignoring the stoichiometry of the reactions given and getting an answer twice the magnitude

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?

- Throughout the course, have students practice mole calculations for substances other than solids.
- Stoichiometry should be re-examined throughout the school year. The balanced chemical equation is still one of chemistry's best tools. Provide suggestions for recognizing limiting reactants in problems.
- Reinforce the use of units and significant figures (especially for addition/subtraction) in problem solving.
- Stress answering the *question that is asked* and do not accept generic answers for all situations (conditions that favor spontaneity, as an example).
- Stress using calculations for the questions that involve math. Have students explain the results if asked to do so.
- Review test-taking strategies for the exam: showing all work, monitoring time allocations, and bringing a calculator. Stress the importance of showing all work, however simple and automatic, when determining an answer. Many students did not appear to have a calculator or they ran out of calculator time by doing the long divisions at the side of the problem.
- Many students are making the statements "$-\Delta H$" and "$+\Delta H$" *cause* spontaneity rather than *favor* spontaneity. The main teaching point is that ΔG determines spontaneity ($-$) and ΔH and ΔS both have an impact on the sign and magnitude of ΔG.
- Do not use shorthand notation that is not universally understood in your classes—for instance, the symbol "ϕ" for mole.

Question 3

What was the intent of this question?

This question tested students' ability to use data from a first-order kinetics experiment to determine the rate constant; determine the half-life; relate the concentration of the reactant to the time of the reaction; use the Arrhenius equation to calculate the activation energy.

How well did students perform on this question?

Approximately 7 percent of the students chose this question. The average score was 1.7 out of a possible 10 points. Points were most often earned in Parts (a), (c), and (d).

What were common student errors or omissions?

Part (a): Most of the students were able to correctly determine the concentration of the colored species, X, at an absorbance of 0.600. Students were split between two methods of determining the initial concentration of the colored species. Beer's Law was correctly used by most students who decided to use that method (this was the most error-free method).

Many students used a proportionality approach, relating the different absorbances at 0.0 minutes and 35.0 minutes to the respective concentrations of X. Errors were common with this method: students set up the proportionality incorrectly, and they made numerous algebra mistakes.

Another common mistake centered around incorrectly changing the determined initial concentration of $12.0 \times 10^{-5}\ M$ to $1.20 \times 10^{-6}\ M$.

Part (b): Problems arose when the students were unable to select the correct expression for the rate law from the given equations sheet. Of those who did select the correct expression, most were able to handle the natural logarithm calculation. A common mistake arose in the final sign of the rate constant. Many students gave a negative value, due to an algebra error. Frequently, one point was earned for the correct magnitude of the rate constant.

The second point of Part (b) was awarded if the correct units for the rate constant were given. This point was rarely earned. Many students included molarity (in many different ways) in their units.

Parts (c) and d): These sections were difficult to grade. Readers found it best to read both c) and d) before determining how many points had been earned. Students were asked to determine the number of minutes required to have the absorbance drop from 0.600 to 0.075 and to determine the half-life of the reaction. Methodology was equally split: Some students used the first-order integrated rate law expression, and some used a method based on inspection of the data.

Students who opted to use the first-order integrated rate law expression usually earned full credit for both parts. Students who answered by inspection of the data and saw that there were two half-lives from 0.0 minutes to 44.2 minutes usually got the correct answer for the half-life. This half-life value was then added to the 44.2 minutes at an absorbance of 0.150 to give 66.2 minutes at the absorbance of 0.075 (another half-life). This approach led to numerous errors. Many students incorrectly determined the half-life by simply taking 44.2 and dividing by 2. This did not earn any points if it was unclear whether the 2 meant 2 half-lives or 2 = 0.150/0.075. The student needed to be clear on how this value was determined.

A point was also awarded for the correct units for the half-life. Many students earned this point.

Part (e)(i): Students were asked to label the vertical axis of the graph provided. This was the most commonly missed point. Incorrect responses included [X], ln[X], absorbance, and 1/[X].

Part (e)(ii): Again, these were a very difficult two points for many students. From their answers, it was clear that many knew that the graph represents the following relationship:

$$\ln k = \frac{-E_a}{R}\left(\frac{1}{T}\right) + \ln A$$

However, many students were not able to explain how to determine the activation energy from the graph. Many took an algebraic approach to describe what variables were known and how the equation had to be manipulated to get a value for E_a.

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?

- Instructors need to show more varied types of kinetics problems.
- Describe to students the characteristics of zero-, first-, and second-order reactions. Students should be able to answer the following:
    - How are graphs used to describe each type of relationship?
    - How are the rate constant and its units determined?
    - How may the equation be used to determine unknown concentrations?
    - How is the half-life determined?

Encourage your students to read questions carefully. Many students did not follow the instruction for part (e)(ii), "Explain how to calculate the activation energy from this graph."

- Repeated emphasis needs to be given to describing how a graphical representation of an equation may be used to obtain useful information.
- Finally, if units are asked for in a problem, then the units will earn points. There were many good papers where the units were completely missing.

Question 4

What was the intent of this question?

This question was designed to assess students' familiarity with chemical nomenclature and knowledge of common classes of chemical reactions, as well as their ability to apply their knowledge in predicting the products(s) of a variety of chemical reactions.

How well did students perform on this question?

The question asked students to choose five of eight reactions. The most popular choices were the displacement of copper ions from solution by aluminum metal (a), the acid/base reaction (c), the precipitation of aluminum phosphate (g), and the production of hydrogen sulfide (h). The mean score was 6.7 out of a possible 15 points.

What were common student errors or omissions?

Reaction (a):
- Failing to dissociate the copper(II) sulfate.
- Producing aluminum sulfate as a product.
- Assigning a charge of +2 to the aluminum ion.
- Reversing the reaction.

Reaction (b):
- Failing to give the correct formula for dimethyl ether.

Reaction (c):
- Failing to represent nitrous acid in the molecular form.
- Writing a double-displacement reaction using non-dissociated compounds.
- Failing to place a negative charge on the nitrite ion.
- Confusing nitrous acid with nitric acid.

Reaction (d):
- Writing gaseous hydrogen iodide as H^+.
- Writing molecular carbonic acid as a product instead of water and carbon dioxide.
- Writing a double-displacement reaction using compounds.
- Failing to dissociate lithium carbonate.
- Producing lithium iodide and HCO_3 as compounds in solution.

Reaction (e):

- Precipitating iron(II) dichromate
- Using the formula for chromate ion instead of dichromate ion.
- Omitting the hydrogen ion as a reactant.
- Failing to recognize a redox reaction.
- Writing dichromate with a −1 charge.
- Writing iron as a product, resulting in two reduction reactions.

Reaction (f):

- Failing to realize that a complex ion was formed.
- Recognizing the complexation but using NH_4 as the formula for the ligand.
- Not knowing the correct formula for ammonia.

Reaction (g):

- Writing the reactants and products using compounds.
- Writing the wrong charges for the reactants and/or the wrong subscript for the phosphate ion.
- Failing to recognize spectator ions.
- Failing to balance the formula for aluminum phosphate.

Reaction (h):

- Writing HCl in molecular form.
- Using SO_4^{2-} and SO_3^{2-} instead of HS^-.

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?

Emphasize that students must:

- know the solubility rules
- know the charges of common cations and anions (including oxoanions)
- recognize the difference between a double-displacement reaction and a net-ionic reaction.
- understand that weak acids are written in molecular form.
- distinguish between acid-base reactions, precipitation reactions, and redox reactions.
- write formulas of compounds correctly
- write only the final net-ionic equation in the given box
- remove spectator ions before writing the final equation

Tell students that the balancing of equations in the AP Exam is time consuming and it is not graded, but the balancing of formulas (subscripts) is required. Also tell them that representing phases of matter is not graded.

Be sure to introduce net-ionic equations early in the course.

Question 5

What was the intent of this question?

The question was intended to probe students' understanding of solubility, precipitation, and qualitative analysis. Students were asked to use solubility data to identify solutions and precipitates and then to describe an experimental procedure, predict the observations based on the procedure, and explain how the observations would be used to identify the two unknown solutions.

How well did students perform on this question?

The question had a maximum score of nine points, with Part (a), Part (b), and Part (c) each having a maximum of three points. The mean score was 5.1 and the mode was 9. The second-most commonly earned score was 6, which was generally obtained when students failed to earn three points in one of two ways: failure to identify precipitates or failure to earn points in Part (c). Most students correctly identified solutions *Q*, *R*, and *S* in Parts (a) and (b), with the fewest points earned in Part (c).

What were common student errors or omissions?

Part (a): Most students correctly identified solution *Q* as potassium carbonate, but many wrote a double-displacement reaction and did not identify which product was the precipitate. Many gave the incorrect formula for silver carbonate (as $AgCO_3$).

Part (b): Credit for this part depends on the student's answer to Part (a)(i). If a student selected NaCl in Part (a)(i), and identified *R* and *S* to be consistent with the observations, full credit was earned; if a student selected $Pb(NO_3)_2$ in Part (a)(i), a maximum of one point could be earned. Another common shortcoming was students' failure to identify the precipitate in Part (b)(ii).

Part (c): This part scored lowest, in general. Common errors included:

- The procedure described by many students was a general qualitative analysis, where they failed to identify a specific reagent that would distinguish solution *X* from solution *Y*.
- Observation of a "reaction" in one solution and not the other earned points, unless that reaction was specifically noted as evolution of a gas, an explosion, etc., without mention of precipitation.
- Incorrect colors of precipitates or solutions were generally ignored in the scoring, even though some unusual colors were mentioned.
- The "correct" observation was to be of a precipitate in one solution but not in the other after addition of a specific reagent. A few students referred to the common ion effect in reducing solubility so that on addition of NaCl to *X* and *Y* (for example) the $BaCl_2$ was said to precipitate, and no precipitate was noted to occur in $AgNO_3$.
- Students often used the word "titration," which meant different things to different students. Sometimes the students meant they would use pH, color, a gravimetric technique, or that they would add a few drops of the reagent to determine *X* and *Y*.

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?

Stress the following content:

- Charges on common ions and the use of these charges in writing formulas of ionic compounds
- Identification of phases in non-ionic equations or writing net-ionic equations
- Common solubility rules

When student are taking the AP Chemistry Exam, encourage them to:

- Read the question through entirely before beginning to answer it. Specific answers should be given whenever possible.

- Connect all parts of a question, where appropriate, to ensure that later answers are consistent with previous ones. For example, many students chose the differentiating reagent in Part (c) as the solution identified as *Q* in Part (a).
- Remember that common charges on ions can be found in the table of standard reduction potentials provided at the beginning of the AP Exam.

Question 6

What was the intent of this question?

The required essay was designed to assess students' knowledge of electrochemistry and to integrate a variety of chemical principles. Students were expected to identify the cathode in a galvanic cell, to calculate a reduction potential, and to use the Nernst equation to determine the effects of changes in concentration.

How well did students perform on this question?

It was apparent that many students were familiar with the material. The mean score for this question was 4.1 out of a possible 10 points. There were many perfect scores. The parts of the question most frequently answered correctly were the identification of the cathode, the electron flow, and the identification of the metal. The least frequently earned points were calculating the reduction potential and interpreting the voltage after concentration changes.

What were common student errors or omissions?

Part (a): Most students earned points for identification of the cathode. The most common errors included the following:

- Students mislabeled the anode and cathode.
- Students confused standard line notation with position of the half cells (anode-left and cathode-right).
- Students identified the electrode as the solution or the container rather than the metal.
- Students failed to recognize that the mass gain was due to Sn^{2+} plating out as Sn metal and incorrectly reasoned that it was due to the movement of electrons into the cathode.

Part (b): Most students earned the point for properly showing the electron flow. The most common error was representing the electron flow through the salt bridge or traveling in some type of complete circuit using the salt bridge.

Part (c): The most common error occurred when students gave an oxidation potential of +0.74 V for Cr metal instead of a reduction potential for Cr^{3+}. Another common error was to combine the data improperly as $E^\circ_{cell} = 0.60\text{ V} - 0.14\text{ V} = 0.46\text{ V}$.

Part (d): Most students were able to identify Cr as metal X regardless of the answer obtained in Part (c). Those not identifying Cr most often chose Fe or some other metal known to possess a 3+ oxidation state. Many students incorrectly identified Cr^{3+} as the metal.

Part (e): The most common mistake was failure to balance mass and charge. Some students failed to remove spectator ions, and some failed to remove free electrons.

Part (f)(i): Many students did not include exponents from the balanced equation when substituting for Q. Some were unable to select the Nernst equation and often chose $\Delta G = -RT\ln K$ or $\Delta G = -nFE$. Students often substituted the total of the solution molarities rather than the number of electrons transferred; some substituted in the reduction potential value from Part (c) instead of the cell potential.

Part (f)(ii): Many students incorrectly reasoned that anything subtracted would reduce the voltage, without recognition that $\ln Q$ was a negative value. Many incorrectly simplified that when the concentration decreases, the voltage decreases.

Parts (f)(i) and (f)(ii) were frequently omitted, even when students had earned all points in Parts (a) through (e).

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?

- Be sure to include a thorough unit on electrochemistry.
- Have students draw, label, calculate, and make observations for galvanic cells and electrolytic cells.
- Have students properly identify anode and cathode and write half-cell reactions for each.
- Make sure that students have the opportunity to describe the flow of electrons and what is actually taking place in each type of cell. Many students had the misconception that electrons were being "pushed" and "pulled" from one cell to another or that protons and electrons were exchanging places, thus accounting for the mass change.
- Students should have the opportunity to perform an electrochemical cell lab and measure voltages.
- Encourage students to read and answer all parts of each question.
- Encourage mathematical reasoning, sign, and magnitude, when dealing with questions involving formulas. Substantial partial credit is earned on this type of question for reasoning based on an equation or an answer obtained in the previous part(s) of the question.
- Make use of the Nernst equation to calculate the E for a galvanic cell.
- Encourage students to fully establish equations before making substitutions.
- Ensure that students understand what each quantity in an equation represents. For example, it is not enough to understand that n is the number of moles if there is no comprehension of what this value actually represents.

Question 7

What was the intent of this question?

This was a broad question designed to assess students' understanding of chemical principles related to intermolecular forces, molecular geometry, and the structure of matter.

How well did students perform on this question?

This was a choice question, selected by approximately 40 percent of the students. The mean score was 2.4 out of a possible eight points. Responses were quite varied. Most points were earned for molecular geometry. Understanding of the variety and terminology of intermolecular forces and the relationship to the observed properties of matter (phase, melting point, solubility) was generally weaker.

What were common student errors or omissions?

Part (a): Students attributed the difference in phase to a difference in melting point without addressing the intermolecular forces, earning 0 points. Some failed to differentiate between covalent bond strength between atoms (intramolecular forces) and intermolecular forces between molecules. Some students correctly identified the substances as being non-polar or having dispersion forces but attributed the difference in strength to molar mass, earning 1 point.

Part (b): Students failed to recognize that NaF and CsCl are ionic compounds and attributed the difference in melting point to a vague concept of bond strength, often implying a degree of covalency between the atoms. Even if they identified the size of the atoms as different, they did not earn any points if they failed to mention electrostatic forces or lattice energy. Those who earned a point for identifying both compounds as composed of ions often attributed the difference in melting points to electronegativity differences rather than interionic distances, so they did not earn the second point.

Part (c): This was the most commonly correct (or partially correct) response. Many students earned points only on this part. The most common error was failing to recognize the correct number of valence electrons in both species. However, students who recognized that the geometry was determined by the number of valence electrons still earned one point.

Part (d): Student responses were most varied on this part. Many compared NH_3 and PH_3 without addressing their interaction with the solvent, water. The question asked about the relative solubilities of the compounds in water, not their relative boiling points. Students who failed to address the interaction with water did not earn full credit.

Those students who treated NH_3 and/or PH_3 as ionic or stated that they dissociated in water did not earn any points. Students who attributed the relative solubilities to basic (or acidic) properties or chemical reactivity of each compound also did not earn any points.

Many students earned one point for attributing the difference in solubilities to the relative polarities of all three compounds without addressing hydrogen bonding. Many others did address hydrogen bonding but did so incorrectly, stating that the intramolecular bonds in NH_3 and H_2O are hydrogen bonds.

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?

- Stress *vocabulary:* atom, ion, molecule; atomic vs. ionic radii; intermolecular vs. intramolecular; ionic vs. covalent; unshared vs. unpaired electrons. Students who incorrectly used these terms or gave vague responses often failed to earn credit.
- Continue to discuss the relationship between chemical principles and experimental/measured properties.
- Generally, students attributed properties of substances in all parts of the question to the position of the elements on the periodic table rather than addressing the question in terms of the principles of atomic and molecular structure. Teachers should stress that the arrangement of the periodic table is a consequence of the structure of the atom rather than the converse.
- Students need practice with this type of question in order to be familiar and comfortable with addressing the properties of *both* species in a comparative situation.

Question 8

What was intended by the question?

This question was designed to test students' knowledge of the structure and properties of CO(*g*) and CO_2(*g*) and kinetic molecular theory. Students were expected to interpret relationships from mathematical formulas and correlate molecular behavior to the formulae.

How well did the students perform?

This was a choice question, selected by approximately 60 percent of the students. The mean score was 3.8 out of a possible eight points. Students earned the points in a variety of ways. Some knew Lewis structures and little else, and others knew kinetic molecular theory of gases but were unable to draw Lewis structures.

What were common student errors or omissions?

Part (a): Most students were able to draw both structures. The more commonly missed structure was the CO structure. A variety of incorrect structures was given for each. Several students drew some of the bonds but did not put in the lone pairs so did not earn the point. Either bond line or dot structures were accepted; however, only complete structures including lone pairs were accepted.

Part (c): Many students omitted the charges and did not earn credit. The gas selected did not have to be listed separately because it was implied when used as a reactant in the equation. Many chose the correct gas but failed to write a correct equation. Some students chose CO on the basis of polarity and "like dissolves like."

Part (d): Neither the magnitude of the slope nor the intercept was essential. This was the most common point earned. Students were very liberal in putting down any graph representation they remembered, from phase diagrams to inverse relationships.

Part (e)(i): Most students knew this relationship. Some knew the relationship but had the wrong justification. $KE = \frac{1}{2} mv^2$ was often used erroneously. Students assumed there was constant velocity and the greater mass of CO_2 indicated a greater kinetic energy for CO_2.

Part (e)(ii): Students who wrote only the root-mean-square speed equation and did not indicate in some way the *m* was for mass did not earn the point. A common error was writing the equation and stating the *m* was for molarity or moles. Students who chose CO_2 because CO_2 was larger or had one additional oxygen atom compared to the CO molecule did not earn the point; those who inserted the mass into the equation and then said CO_2 was slower earned the point. Many students gave the relationship but no justification, thereby not earning the point. Many effectively used Graham's Law to justify the relationship, and many indicated greater pressure pushed molecules faster.

Part (e)(iii): Many students recognized there would be fewer CO_2 molecules but gave an incorrect reason. Many others indicated there would be more CO_2 molecules because CO_2 was larger or has one additional O atom compared to the CO molecule. Another common response was more CO molecules, because they are smaller and therefore one can pack more into the space provided. Many students gave the relationship and no justification, thereby not earning the 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?

- Continue to teach acceptable formats for Lewis structures. Make sure to also cover how to deduce correct geometries for molecules. Students were very creative at assigning geometry shape names to CO_2.
- Continue to teach balancing equations and emphasize that an ion's charge is an integral part of its formula and charges need to be kept on ionic species in an aqueous solution.
- Continue to help students visualize a model of a gas. Many students do not understand how external factors can affect a gas. Teach the kinetic molecular theory of gases and how each theory relates to the properties of gases. Many students did not recognize what the root-mean-square speed referred to. Students also did not recognize the difference between external pressure and internal pressure being exerted. Reinforce molecular size as being irrelevant to ideal gas relationships.
- Continue to have students graph relationships and develop visuals to help them understand relationships. Students should recognize the difference between direct, indirect and exponential graphs.
- Emphasize to students it is to their benefit to write clearly.
- Continue to stress proper explanations with your students. For example: "bigger" and "smaller" are not the same as "heavier" and "lighter." Also refrain from letting your students use pronouns. The Reader does not know what "it" refers to— do not assume that he or she can read a student's mind.
- Continue to ask students "why" by requiring justifications. Emphasize to them that one-word answers are not considered justifications—they need to complete their thoughts.
- Remind students to answer the entire question. Many times a correct relationship did not earn points because the justification was missing.
- Ask students to derive relationships from mathematical equations without doing the math.