CollegeBoard AP

Student Performance Q&A:

2011 AP® Chemistry Free-Response Questions

The following comments on the 2011 free-response questions for AP® Chemistry were written by the Chief Reader, Larry Funck of Wheaton College in Wheaton, Ill. 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 and ability to solve problems and explain concepts that pertain to acid/base equilibrium and buffers. Parts of the question required calculation. Students were presented with three samples of equal volume and concentration — a strong acid, a weak base and the conjugate acid of the weak base. Part (a) asked students to determine the pH of the solution of the strong acid and assessed their understanding of the pH scale. Part (b) required students to write the equilibrium expression for the hydrolysis reaction of the weak base and to determine the hydroxide ion concentration in the solution, given the concentration and the value of K_b for the weak base. Part (c) required students to determine the value of the K_a of the conjugate acid. Students then were told that the solutions containing the weak acid and weak base were combined and that they were to determine the pH of the resulting solution. To do so they needed to apply any of the equilibrium equations for K_b, K_a or the Henderson-Hasselbalch equation appropriately. All three solutions were then combined, and part (d) required students to state with justification whether this solution would be an effective buffer and to determine the concentration of the weak acid in this resulting solution.

How well did students perform on this question?

Students did reasonably well on this question, earning a mean score of 3.65 out of a possible 10 points and showing a broad distribution, with many students earning 4 or 5 points. Approximately 12 percent of students failed to address the question or earned no points, while 1.4 percent earned full credit. Most frequently, students earned all their points early in the question, and it was comparatively rare that a response would fail to earn points on a given part and then earn points on subsequent parts of the question. The large percentage of scores of 4 typically earned all 4 points on parts (a), (b)(i) and (b)(ii) and failed to earn points on subsequent parts of the question. Those responses that earned 5 points usually earned them all on parts (a), (b) and (c)(i).

Students were generally successful on part (a), earning 1 point for the correct pH of a 0.100 M HCl solution, and in part (b), writing a correct expression for K_b of NH_3, substituting appropriate values into the

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equation, and solving to determine the correct [OH^-]. A small but significant percentage of responses set up a correct equation but did not solve correctly. Most papers made the simplifying assumption that the $[NH_3]_{equilibrium} \approx [NH_3]_{initial}$ and did not need to solve a quadratic equation.

A range of approaches were taken on part (c). Many students recognized that $K_a = K_w/K_b$ in part (c)(i). Others were able to determine the value of K_a from the expression and the concentrations of species in beaker 2, previously determined. Regardless of the answer to part (i), part (ii) was much more challenging for the students. Most incorrect responses failed to recognize that the resulting solution was a buffer. Those responses that correctly indicated that $[NH_3]_{equilibrium} = [NH_4^+]_{equilibrium}$ generally went on to earn credit.

Part (d)(i) was the least often earned point; few students referred to the stoichiometry of the reaction. Credit in part (d)(ii) was also rarely earned. Students attempted to use equilibrium equations to answer a question that was based on stoichiometry.

What were common student errors or omissions?

Part (a):

- Not recognizing HCl as a strong acid
- Confusion between concentration and moles

Part (b):

- Incorrect chemical formulas, omission of charges on ions in equilibrium expression
- Including [H_2O] in equilibrium constant expression for K_b
- Not recognizing that $[OH^-]_{equilibrium} = [NH_4^+]_{equilibrium}$
- Arithmetic errors, particularly involving scientific notation

Part (c):

- Not recognizing the relationship between K_a and K_b — attempting to determine value of K_a from given concentrations
- Not recognizing the resulting solution as a buffer and treating it as a weak acid or weak base
- Adding (or averaging) the pH values for beaker 2 and beaker 3

Part (d):

- Making general assertions without accounting for stoichiometry (e.g., "The solution is not a buffer because HCl is a strong acid")
- Neglecting the reaction of HCl and NH_3 as a source of NH_4^+
- Neglecting the effect of dilution on concentrations

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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?

Suggestions for teachers:

- Distinguish between amount (moles) and concentration (molarity = mol/L). Reinforce notation that "[ ]" refers to the molar concentration of a species.
- Demonstrate or provide a laboratory exercise to familiarize students with the pH scale.
- Emphasize the distinction between an equilibrium constant <u>expression</u> and its <u>value</u>.
- Practice identifying buffers — have students make up buffers in different pH ranges.
- Demonstrate that a buffer can be treated as a weak acid in equilibrium with its conjugate base OR as a weak base in equilibrium with its conjugate acid, and that the approaches are equivalent.
- Require clear work shown on calculated answers — stress process rather than memorization of formulas.

Suggestions for students:

- Read and answer the questions that are asked.
- Be sure that numerical answers are reasonable.
- Differentiate between moles and concentration (moles/liter).
- Practice writing clear, expository statements regarding chemical systems.
- Use vocabulary correctly.

Question 2

What was the intent of this question?

This question assessed students' knowledge and skills pertaining to a laboratory experience involving the determination of the mass percent of silver in a copper-silver alloy. The question consisted of both mathematical and conceptual applications of chemistry. Part (a) was primarily concerned with the laboratory process itself: diluting an acid (a mathematical determination and an experimental process in which students are provided with a specific list of equipment), comparing and contrasting appropriate glassware based on the level of precision of the dilution, and cleaning up an acid spill. Parts (b) and (c) focused on the manipulation of experimental data: students determined the number of moles of AgCl precipitate and the mass percent of Ag in the Cu-Ag alloy.

How well did students perform on this question?

The mean score was 3.51 out of a possible 9 points. Approximately 26 percent of students earned a score of 3 or 4, 14 percent earned no points or did not address the question, and only 1 percent earned the maximum score. Students generally answered all parts of the question, with most of the points being earned in part (a)(i) for correctly calculating the volume of concentrated HNO_3 needed to prepare 50 mL of a 6 M HNO_3 solution and in part (c) for recognizing that the mass percent of Ag in the alloy was based on the mass of the alloy. Students had a difficult time expressing themselves in parts (a)(ii) through (a)(iv) and determining the correct mass for the dried AgCl precipitate in part (b).

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What were the common student errors or omissions?

A large majority of students correctly answered part (a)(i). The most common error was the incorrect algebraic manipulation of the $M_1 V_1 = M_2 V_2$ equation in order to solve for the volume of HNO_3 needed for the dilution. This incorrect expression resulted in the common answer of 133 mL of 16 M HNO_3 needed for the dilution. Acceptable values reported for the answer in part (a)(i) include 20, 19, 18.8 and 18.75 mL.

In part (a)(ii) students could earn 1 point based on the procedure used to carry out the dilution. Many students seemed to experience a disconnect between the mathematical and the experimental processes associated with the concept of dilution. For example, students who calculated a volume of 133 mL HNO_3 were required to prepare the 50 mL solution in part (a)(i) did not realize (or chose to ignore) that this volume of concentrated HNO_3 was too large for the 100 mL graduated cylinders (or beaker) and also too large for a total solution volume of 50 mL. Students also incorrectly performed the dilution process by starting with 50 mL of water and then adding the acid. They incorrectly used the 100 mL beaker to measure the volume of water or acid used in the dilution. Whether their result in part (a)(i) was correct or not, many students did not specify the volume requirements of either the acid or the water when conducting the dilution. Although no penalty was given, many students used the eyedropper to deliver their calculated volume of acid or water to the graduated cylinder.

The second point students could earn was based on addressing the safety precautions needed to carry out the dilution. Most students listed “put on safety goggles and rubber gloves” on the first line of their response but often incorrectly “poured water into acid.” A variation of this error occurred when students neglected to specify the order of mixing, such as “pour the acid and water into the beaker for mixing.”

In part (a)(iii) the most common error was not recognizing that the relative precision of the glassware should be compared to the level of precision needed for the diluted acid. Students also indicated unfamiliarity with the volumetric flask by suggesting that diluting the acid in the flask may result in an overflow (spillage). Additionally, students often preferred the graduated cylinder over the flask because the cylinder has gradations, whereas the flask has only a single calibration line. Some students thought that the graduated cylinder was a more precise instrument with which to measure volume (i.e., the misconception that more gradations yield better precision). Another common error was associating the volumetric flask with a specific experiment, such as titration, or a process, such as the dissolution of a solid. Some students argued that the calculated volumes of acid and water (19 and 31 mL, respectively) were accurate to only ±1 mL and thus that the graduated cylinders were more appropriate to use.

In part (a)(iv) there were two primary sources of error. First, students chose the incorrect solution (water or NaCl) to clean the acid spill; second, students tried to justify why $NaHCO_3$ would be the best option by stating that the $NaHCO_3$ would lower the pH (correlating a decrease in H^+ with a decrease in pH), indicating that the $NaHCO_3$ could be used to clean the acid spill because it is a buffer, or stating that the $NaHCO_3$ “diluted” or “absorbed” the acid.

In part (b) the most common mistake for the first point was taking an average of the masses after each drying and then subtracting the mass of the dry crucible from the average. Overall students did a very good job of correctly converting from grams of AgCl to moles of AgCl. The most common mistake for the second point was reporting the moles of AgCl with the improper number of significant figures. Since students were manipulating experimental data, they were held stringently to the proper number of significant figures. Many students did not use the molar masses (or all of the significant figures in the molar masses) provided to them in the periodic table (143 g/mol was common).

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In part (c) the most common mistake for the first point was incorrectly using the mass of AgCl from part (b) in the mass percent calculation. For the second point some students did not recognize that the mass percent was based on the initial mass of the alloy. A general misconception was that the Cu-Ag alloy was a compound ("CuAg") with a 1:1 mole ratio and therefore that the mass percent of Ag is determined based on atomic masses, $\left(\frac{\text{atomic mass Ag}}{\text{atomic mass Cu + atomic mass Ag}}\right) \times 100\%$. Another common mistake was calculating the mass percent of Ag in AgCl.

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

Suggestions for teachers:

- Do multiple labs throughout the academic year. Based on student responses, it seems as though students may not be doing enough laboratory exercises.
- Have students become familiar with common glassware (uses, applications, and precisions) and review basic laboratory procedures. Emphasize the concept of significant figures providing information pertaining to the quality (precision) of the measurement.
- Emphasize all safety procedures for safe lab practices.
- Encourage students to review their lab notebooks prior to taking the exam.
- Require work with units (dimensional analysis).
- Review the rules for determining the significant figures expressed in measured (experimental) and calculated ($+, -, \times, \div$) values.
- Review a prior year's exam with your students. Show students where to find the information that is provided to them in the exam.

Suggestions for students:

- Never measure volumes with a reaction vessel, like a beaker or an Erlenmeyer flask. All volume measurements must take place in a calibrated instrument (graduated cylinder, volumetric flask, volumetric pipet, etc.).
- If you are asked to select the best answer, make a single selection and justify the reasoning for making that choice.
- If you are asked to make a comparison, mention both possibilities and then make a single choice with accompanying justification.
- Be cognizant of significant figure rules and how to apply them correctly.
- Show all your mathematical work and make sure to include units. Analyzing the units can help you determine if you have done the correct calculation.
- Familiarize yourself with the resources provided to you in the exam booklet.
- DO NOT write your answers in the body of the question; write them on the lined pages.
- Skip a line between subsections for clarity and ease of evaluation
- Your written, nonmathematical, answers should be neat and concise responses.

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- Remember, AP Readers can best grade your exam if you write clearly and use proper grammar. Write in pencil or blue-ink pens and avoid using pens that smear easily.

Question 3

What was the intent of this question?

This question assessed students' understanding of selected concepts of thermochemistry, electrochemistry, and environmental chemistry. Thermochemistry concepts included the determination of a standard enthalpy change, applications of Hess's law, and stoichiometric determination of heats of reaction given mole or mass amounts. Electrochemistry concepts included the determination of cell reactions from half-cell reactions, the determination of standard cell potentials from half-cell potentials, and applications of Faraday's law. Finally, students were asked about the potential impact of carbon dioxide emissions on global climate.

How well did students perform on this question?

The mean score was 3.18 out of a possible 10 points. The most common score was zero. Part (a) was the most accessible part of the question. The point was lost for mechanics (off by a factor of two, wrong sign, or no units) more than for conceptual misunderstandings. Students had few conceptual problems with part (b) as well. This is probably because "heat" is more tangible than "enthalpy." Still, about 10 percent of students, upon seeing "mass" and "heat" in the question, used the heat transfer equation, $q = mC\Delta T$ instead of $q = n\Delta H$. Part (c) was the least accessible thermochemistry point. The most common wrong answer was +88.0 kJ, which indicated a lack of understanding of thermochemical principles (application of Hess's law).

Students were slightly less successful with the electrochemistry parts of the question than they were with the thermochemistry parts. On the other hand, a number of students who were unable to do the thermochemistry parts were able to do the electrochemistry parts successfully. Some students had difficulty properly combining half-cell reactions in part (d). About 30 percent of the responses left water molecules, hydroxide ions, or electrons on both sides of the equation.

About half the students correctly computed the cell potential in part (e). Many of those who erred added a minus sign, dropped the units, or multiplied the anode half-cell potential by two. Over half the students struggled with the stoichiometric conversion required to find moles of electrons from moles of hydrogen in part (f)(i). In part (f)(ii), over half were insufficiently familiar with Faraday's law calculations: (moles of substance $\rightarrow$ moles of electrons $\rightarrow$ charge in coulombs $\rightarrow$ current in amperes). Finally, part (g) was the least accessible part. It required a familiarity with the concept of global warming or an enhanced greenhouse effect thought to be caused by carbon dioxide emissions.

What were common student errors or omissions?

Part (a):

- Not multiplying the standard molar enthalpy of formation of water, ΔH_f°, by two
- Dropping units (only kJ, kJ mol^{-1}, or kJ/mol$_{rxn}$ were accepted)
- Dropping the negative sign
- Not using zeroes for the standard enthalpies of formation of elements

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Part (b):

- Not converting grams to moles
- Not recognizing that the standard formation reaction of liquid water is the same as the standard combustion reaction of gaseous hydrogen
- Using 1.008 g mol^{-1} as the molar mass of H_2
- Using the answer to part (a) for the standard enthalpy of combustion of one mole of H_2 (instead of two moles of H_2)
- Not showing the calculation setup
- Using the heat transfer equation ($q = mC\Delta T$) to determine the heat of combustion

Part (c):

- Giving the enthalpy of vaporization of two moles of water (+88.0 kJ) instead of the enthalpy of combustion of two moles of hydrogen to give two moles of water vapor (–571.6 kJ + 88.0 kJ = –483.6 kJ) for the final answer
- Not multiplying the standard molar enthalpy of vaporization of water, ΔH°_{vap} , by two

Part (d):

- Not correctly balancing the equation
- Not canceling two moles of water (i.e., 2 $H_2O(l)$ + 2 $H_2(g)$ + $O_2(g)$ = 4 $H_2O(l)$)
- Not canceling electrons, hydroxide ions or both
- Reversing the reaction

Part (e):

- Not reversing the sign of the oxidation half-cell potential (giving $E°$ = –0.43 V)
- Reversing the sign of the reduction half-cell potential (giving $E°$ = –1.23 V)
- Reversing but doubling the oxidation half-cell potential (giving $E°$ = +2.06 V)
- Reversing both and doubling the oxidation half-cell potential (giving $E°$ = +1.26 V)
- Dropping the units
- Not showing the calculation setup

Part (f)(i):

- Using the wrong mole ratio of moles e^- to moles H_2
- Not showing the calculation setup
- Not using 0.93 mol H_2 in the calculation
- Wrongly attempting to use the cell potential from part (e) ($\Delta G° = -nFE°$)
- Multiplying the given 0.93 mol H_2 by the molar mass of H_2
- Finding the total number of e^- (instead of moles of e^-)

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Part (f)(ii):

- Not indicating the conversion of moles of e^- to charge in coulombs using the Faraday constant
- Not dividing the charge in coulombs by the time in seconds to obtain current in amperes
- Wrongly dividing by 96,500 C/mol e^-, multiplying by 600. s, or both
- Not showing the calculation setup
- Dropping the units

Part (g):

- Not specifically identifying carbon dioxide or CO_2 as the substance most likely to cause an environmental disadvantage in the butane fuel cell
- Not identifying the specific environmental phenomenon potentially affected by carbon dioxide (global warming, the greenhouse effect, climate change, and acid rain were all accepted)
- Wrongly identifying a harmful effect of carbon dioxide on the ozone layer as the environmental disadvantage

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

Suggestions for teachers:

- Have students practice more problems using thermochemical equations.
- Have students manipulate thermochemical equations by adding, subtracting, reversing, or multiplying them by stoichiometric factors.
- Have students practice applying Hess's law of constant heat summation.
- Have students practice more problems using electrochemical cells.
- Make sure students understand that volts are intensive units (joules per coulomb) whereas joules and kilojoules are extensive (i.e., doubling a chemical reaction doubles its energy or enthalpy in kilojoules but does not double its cell potential in volts).
- Have students practice writing cell reactions from half-cell reactions and decomposing cell reactions into anode and cathode half-cell reactions with the appropriate numbers of electrons.
- Make sure students understand the accepted practice of canceling nonparticipating species from both sides of a chemical equation, and of reducing coefficients to the lowest set of whole numbers.
- Have students practice some simple Faraday's law calculations (e.g., they should be able to convert from moles of reacting species to moles of electrons to charge in coulombs to current in amperes, and back again).

Suggestions for students:

- Show your work explicitly on all calculation problems.
- Remember that units of quantities are important and may be manipulated algebraically throughout a calculation.
- On calculator questions a numerical answer is required; showing a setup is not sufficient.

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- Use the lined space allowed for answers instead of cramping a few numbers between the lines of a question.

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 communicating how these substances react with one another in the form of a balanced net-ionic equation. Additional aspects of the problem evaluated general understanding of chemical concepts presented to students in the classroom and the laboratory.

How well did students perform on this question?

The mean score was 6.62 out of a possible 15 points. Students displayed a wide range of knowledge and skills in their responses to this question. The scores covered the entire scale and had a relatively normal distribution. The most common scores were in the 5–7 range. Approximately 1.4 percent of the responses earned a score of 15, and there were very few blank responses.

What were common student errors or omissions?

Part (a):

- Writing solid species in ionic form
- Not determining the oxidation state of magnesium from the periodic table. Nearly 10 percent of students used Mg^{1+}.
- Incorrect products of an acid base (neutralization) reaction
- Not recognizing that strong acids are completely ionized in solution
- Not recognizing that soluble ionic species are completely dissociated in solution
- Inability to correctly recall solubility rules
- Not reducing coefficients to lowest terms
- Inability to recognize that the volume calculation depends on the 2:1 stoichiometry of OH^- : $Mg(OH)_2$ in addition to the 1:1 stoichiometry of H^+:OH^-
- Incorrect application of the 1:1 stoichiometry of H^+:OH^- taken directly from the net-ionic equation
- Application of the molar volume at STP (22.4 L/mol) rather than the molarity of the hydrobromic acid in an attempt to calculate the volume
- Converting from liters to milliliters incorrectly

Part (b):

- Lack of familiarity with coordination chemistry. The most common accepted response was $Co^{2+} + 2Cl^- \rightarrow CoCl_2$. Readers were certain that most students actually intended this as a precipitation reaction rather than an aqueous uncharged complex. Several students confirmed this by indicating the state of $CoCl_2$ as (*s*).

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- Not recognizing that strong acids are completely ionized in solution
- Not recognizing that soluble ionic species are completely dissociated in solution
- Inability to correctly recall solubility rules
- Inability to correctly recall the formula and charge for the nitrate ion
- Not calculating the correct overall charge on a complex ion
- Not recognizing Cl^{-} as the preferred ligand for the complex
- Attempting to produce a coordination complex by simply combining a variety of incorrect reacting species together
- Not understanding the term “Lewis base”
- Confusing Lewis acid-base theory with that of Brønsted and Lowry or Arrhenius.

Part (c):

- Not using the table of standard reduction potentials to determine the most likely redox reaction to occur. Approximately 15 percent of students oxidized Cu to Cu^{1+}.
- Not recognizing that soluble ionic species are completely dissociated in solution
- Inability to correctly recall solubility rules
- Inability to correctly recall the formula and charge for the nitrate ion
- Inability to correctly recall the symbol for silver and, less frequently, copper
- Not reading the question carefully and not answering what was asked. Approximately 10 percent of students gave a description of electron transfer processes or single replacement reactions rather than giving an observation.
- Giving incomplete observations such as “color change” or “precipitate forms”

All parts:

- Writing complete balanced formula (molecular) equations instead of net-ionic equations
- Writing complete ionic equations rather than net-ionic equations
- Writing miscellaneous charges over formulas in the box
- Writing several equations in the box (only the last equation gets scored)

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

Suggestions for teachers:

- Give students practice balancing equations not only for mass, but also for charge. A routine of checking for the balance of both should be established.
- Offer students practice writing chemical formulas for molecules, atoms and ions in solution. Stress that all soluble ionic compounds should be dissociated and any of the six strong acids should be ionized. All other species, such as elements or covalent (molecular) compounds, should not be written as ions.

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- Encourage students to use the position of an element in the periodic table to determine its ionic charge.
- Remind students frequently that all nitrate compounds are soluble and hence dissociate in solution.
- Remind students that neutralization reactions and coordination complex formation reactions do not involve oxidation or reduction of any species.
- Expose students to some coordination chemistry. They need to recognize common ligands and practice writing acceptable coordination compounds with appropriate charges.
- Encourage students to use the table of reduction potentials provided to help them write a correct redox reaction.
- Remind students 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.
- Practice the application of stoichiometry frequently throughout your course. Emphasize the importance of considering the source of the reacting species rather than applying the stoichiometry of the net-ionic equation. Use reactions that involve polyprotic and polybasic species often.
- Students remember what they see and do better than what they hear and read. Do laboratory work and frequent demonstrations to help students learn common reactions and practice equation writing.
- Stress the recording of qualitative observations during laboratory work.

Suggestions for students:

- Cancel out common species that are present in both the reactants and the products. Practice writing net-ionic equations in boxes for this question.
- Reduce the stoichiometric coefficients to lowest whole numbers. Multiply fractional coefficients for lowest whole numbers as well.
- Learn the names and symbols of the common elements. Silver is not Au or Si.
- Know the formulas and charges for common polyatomic ions. An error in the formula of nitrate could have led to points lost in parts (b) and (c).
- Become very familiar with the list of the six common strong acids. Many students presented HBr, HCl, and HNO_3 as weak acids. Others indicated that hydrobromic acid was $HBrO_3$ or hydrochloric acid was $HClO_4$. These misconceptions led to points lost in parts (a) and (b).

Question 5

What was the intent of this question?

This question asked students to complete the Lewis diagram for the N_2H_4 molecule in part (a). Part (b) asked students to determine, based on their diagram, whether all six atoms were on the same plane and to justify their answer. Part (c) gave students the boiling points for N_2H_4 and C_2H_6 and asked them to explain the difference in boiling points in terms of the intermolecular forces in each liquid. In part (d) students wrote a balanced chemical equation for the reaction between N_2H_4 and water to explain a pH greater than 7. Part (e) gave students a balanced chemical equation for hydrazine reacting in air and asked them to identify the type of reaction and justify their answer. In part (f) students were asked to refer to the

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equation provided in part (e) and predict the sign of the entropy change, with justification. In part (g) students were given a statement regarding energy and the breaking of bonds and were asked to justify whether the statement was true or false.

How well did students perform on this question?

The mean score was 3.04 out of a possible 8 points. Students generally attempted all parts of the question, with most of the points earned in part (a) by completing the Lewis diagram, in part (b) by identifying the arrangement of atoms or by citing electron-pair repulsion, in part (e) by identifying and justifying an oxidation-reduction reaction, and in part (f) by assigning an appropriate sign to entropy with a valid justification.

What were common student errors or omissions?

In part (a) some students expanded the octet of nitrogen and drew a structure with a double or triple bond and occasionally with additional lone electron pairs. A few students completed an octet for each atom, including hydrogen, and seemed to show all electrons, not just valence electrons. Occasionally structures included lone electrons in a variety of locations.

In part (b) students often gave an incomplete justification for why all six atoms were not on the same plane. A statement that lone electron pairs are present is a fact and does not provide an explanation for the geometry of the molecule. Some students described the two-dimensional image on the paper, citing that two hydrogen atoms were below the nitrogen atoms and two hydrogen atoms were beside the nitrogen atoms, for an incorrect justification. Some did not seem to tie the structure drawn in part (a) to the explanation for part (b).

Part (c) was difficult for many students. One common omission was discussing the intermolecular forces of only one of the two molecules. Another common error was the confusion between intramolecular and intermolecular forces. Students often referred to the breaking of covalent bonds when the substance boils. Students with an incorrect structure in part (a) showing a multiple bond often referred to multiple-bond strength versus single-bond strength, clearly indicating a misunderstanding of boiling as a phase change. More often, however, students referred to the hydrogen bonds between the N and H atoms in the molecule and did not make a clear distinction that IMFs are forces between molecules. The covalent bonds between the N and H were erroneously identified as hydrogen bonds, and many students stated that the hydrogen bonds in N_2H_4 were much stronger than the covalent bonds in C_2H_6. Another common omission was identifying the intermolecular forces in each molecule but making no meaningful comparison between them.

In part (d) a variety of products were written for the reaction between hydrazine and water. Some of those included NH_3 and OH^{2-}, N_2H_6 and OH^-, H_3O^+ and $N_2H_4^-$, and a complete decomposition into elements. One common omission was leaving out charges on ions in solution.

In part (e) a common omission was identifying only one species as oxidized or reduced. A common error was assigning an incorrect oxidation number to nitrogen without referring to the appropriate companion process or identifying a net oxidation number change. Some students identified oxidation number changes for three species — H, N, and O — in the reaction. There were some vague answers that simply stated that the reaction was oxidation-reduction since atoms change charge, with no specific identification. The most common incorrect answer was citing a decomposition reaction because N_2H_4 decomposed into N_2. Another common error was for students to provide a rationale by eliminating the choices of acid-base or decomposition but never explaining why the reaction is an oxidation-reduction reaction. Occasionally students reversed which species were oxidized and reduced. Another common error was identifying N_2, a product, as a species oxidized.

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One common omission in part (f) was failure to indicate the type of reactants and products; a statement of an increase in moles of product without mentioning the state did not receive credit. Also, a common reference to a "phase change" of the liquid hydrazine to a gaseous form, rather than the chemical process, did not earn the point. Another common error was for students to explain that because $\Delta H°$ was negative, the entropy must be positive, even though no reference was made to $\Delta G°$ in the question, or simply substituting sign values into $\Delta G° = \Delta H° - T\Delta S°$.

Many students indicated that the statement in part (g) was true. The misconception that energy is released when bonds are broken still exists. A common error was a discussion of energy required to break bonds leading to a conclusion that the given $\Delta H°$ should have been reported as positive instead of negative, thereby failing to recognize that the value of $\Delta H°$ is the combination of the endothermic breaking of bonds and the exothermic formation of bonds. Some students cited the negative $\Delta H°$ value as proof that the reaction was actually endothermic.

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 impossible to overemphasize the importance of writing precisely. Vague and unclear answers often made it impossible for AP Readers to determine whether the student understood the chemistry. Clear, precise, and succinct prose does not come naturally; we all must work on this and hold our students accountable for use of correct terminology. Students often referred to intermolecular forces as bonds, making it difficult to distinguish between intramolecular and intermolecular. When justifying answers, statements of fact are not enough; an explanation of "why" must be provided.

Suggestions for teachers:

- Do not accept incorrect terminology from students.
- Give students practice balancing a variety of reactions stoichiometrically as well as balancing for charge.
- Encourage students to explain and justify answers for all types of questions. Though time is required to score student responses, explanation, and justification are very important components in assessing understanding and misunderstanding.
- Allow students the opportunity to explore misconceptions in chemistry.
- Intramolecular and intermolecular interactions are always difficult for students to distinguish or describe. Part (c) provided evidence that the confusion continues. Work with students to help them understand these concepts. It may be helpful to have students organize thoughts into categories when addressing this type of question:
    - Identify the major binding force first (ionic, covalent, metallic).
    - Identify types of intermolecular attractive forces if appropriate.
    - Emphasize that the term "van der Waals forces" is a general term that includes all IMFs, and have students identify the types of van der Waals forces.
    - Allow students to explain differences in data using the principles of bonding, IMFs, or both.
    - Have students illustrate attractions between molecules and clearly identify the binding forces and the intermolecular forces.

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Suggestions for students:

- Read the question carefully and answer the question asked. Begin by writing the answer and then provide supporting evidence.
- Often information is used for multiple parts of a question; be sure to refer to information that is given.
- When responding to the question of whether a statement is true or false, begin by writing down one of these choices and then provide supporting evidence. Do not begin the answer with the word "yes."
- Be sure to address each substance within a given question stem. When asked to compare two substances, always talk about both. Simply discussing one and expecting the reader to assume that the other is implied will not receive credit.
- Use appropriate language when answering questions. It is not acceptable to refer to an atom as a "molecule" or to refer to an intermolecular force as a "bond."
- When drawing Lewis structures, take time to calculate the total number of electrons before beginning.
- When writing balanced equations, pay attention to details such as balancing the charges. Ions written without charges receive no credit.
- Avoid vague generalizations when answering questions. Give details as often as possible.
- Write legibly and be sure to write all answers in the lined spaces provided instead of squeezing words between question parts.

Question 6

What was the intent of this question?

There were two parts to this question. The first part explored the concept of dynamic equilibrium with respect to vapor pressure. In part (a) students had to recognize that at the given temperature, when the volume of liquid was no longer changing, the system was at equilibrium. In part (b) students needed to invoke two of three arguments that used kinetic molecular theory to explain why an increase in temperature would increase the pressure in a fixed volume. The second part of the question explored a decomposition reaction with graphical data. In part (c)(i) students used the graphical data to determine that the reaction was zero order. In part (c)(ii) students wrote the correct rate law for the reaction. In part (c)(iii) students used graphical data from the first graph for a correct setup with units for the value of k, the rate constant. In part (d) students were asked to compare the pressure in the flask before and after the reaction took place.

How well did students perform on this question?

The mean score was 2.98 out of a possible 8 points. Students generally attempted all parts of the question. If parts were omitted it was generally part (a) or part (c)(iii). Many students earned just 1 point in part (b). Of the points missed, they commonly were missed in all parts of (c). Approximately 13 percent of students either earned no points with their response or failed to address the question, while 2 percent achieved a score of 8.

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What were common student errors or omissions?

In part (a) students needed to make a connection between observation (the constant volume of the ethanol) and the conclusion (the system is at equilibrium). Common errors included the following:

- Not making a choice of greater than, less than, or equal to 100 torr
- Trying to use gas law arguments for pressure and temperature
- Stating that the amount of ethanol remained constant so the pressure remained the same
- Stating that because everything was constant, the pressure of 100 torr would also be constant, with no mention of equilibrium
- Stating that at equilibrium, the lack of change of pressure was due to the lack of change on the molecular level (i.e., no evaporation or condensation occurred)

In part (b) answers had to be in terms of kinetic-molecular theory to earn full credit. Common errors included the following:

- Talking about the electrons or atoms instead of molecules (i.e., blurring the distinctions between electrons, atoms, and molecules).
- Not clearly explaining that an increase in kinetic energy results in more gas molecules moving faster, which results in more molecules colliding with the walls of the flask and colliding with a greater force
- Using language such as "more intense collisions" rather than harder collisions, or "excited atoms" (or electrons) rather than faster-moving molecules
- Recognizing that kinetic energy increased with increasing temperature and that the particles move faster and collide with the walls of the flask more frequently, but just restating the phrase and giving it as a second reason
- Listing speed, energy, and frequency as separate reasons for increased pressure
- Invoking collisions between molecules, rather than collisions with the wall of the flask, as a reason for increased pressure
- Stating that the volume decreased so the pressure had to increase
- Applying strictly gas law arguments, ignoring KMT
- Writing incorrect statements, such as:
    - "The gas expanded thus increasing the pressure."
    - "The increase in temperature caused the molecules to expand" (sounding like the molecules swell).
    - "The molecules collide with each other to cause an increase in pressure" (rather than collide with the walls of the container).
    - "As temperature increases, volume increases, but since it is in a rigid container, pressure goes up instead."
- Treating the phase change as a reaction and using activation energy and heats of reaction for reasons

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Part (c)(i):

- Trying to identify the reaction order that each graph represented rather than picking the first graph, which clearly represented a 0 order reaction (because of the straight line plot of [ethanol] versus time)
- Writing that the slope is either +1 or −1 (rather than linear) to describe the [ethanol] versus time graph
- Identifying the [ethanol] versus time graph as indicating a first-order reaction

Part (c)(ii):

- Correctly identifying the order of the reaction as 0 but not writing the corresponding rate law
- Including the products in the rate law equation
- Writing an equilibrium expression for the rate law
- Writing the integrated rate equations rather than the rate law equation
- Writing the first-order rate equation after identifying the reaction as zero order

Part (c)(iii):

- Using concentration brackets to represent units or moles rather than moles/liter
- Omitting units even though the question specifically asked for units
- Incorrectly substituting values for rate into the rate equation when solving for k, the rate constant:
    - Using a single data point for the rate
    - Using seconds for the rate
    - Using molarity for the rate

Some students correctly stated that the reaction was zero order in part (c)(i), wrote the rate law incorrectly in part (c)(ii), but then interpreted the graph correctly and were able to calculate the value of k with correct units and earned 2 points in part (c)(iii).

Part (d):

- Trying to make this a $PV = nRT$ problem or a Boyle's law problem by pulling 2.0 L, 1.0 L, and 100 torr from other parts of the question
- Stating that because the ethanol completely decomposed, the pressure dropped to zero, or that the flask is empty so the pressure = 0.
- Stating that the pressure is constant so the final pressure is 0.40 atm

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?

- Help students understand the connection between constant observable properties and a system at equilibrium — dynamic equilibrium.
- Make sure that students can interpret graphical data.

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- Remember to teach zero order reactions.
- Make sure that students give a reason for their choice.
- Remind students to carefully read the questions.
- Teach students the difference between a rate law, an integrated rate law, and an equilibrium expression, and to distinguish between rate and time.
- Teach students what [ ] represents. It was clear that many students did not know how to write the rate law equation.
- Teach what concentration brackets represent. Help students understand that [ ] (concentration brackets) are not units.
- Teach students to set up the problem, substitute the numbers in, and then do the calculation. Often in a noncalculator problem, if the work was clearly shown, a point would be earned even when a computational error was made.

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