Student Performance Q&A:

2016 AP® Chemistry Free-Response Questions

The following comments on the 2016 free-response questions for AP® Chemistry were written by the Chief Reader, Roger Kugel of the University of Cincinnati. They give an overview of each free-response question and of how students performed on the question, including typical student errors. General comments regarding the skills and content that students frequently have the most problems with are included. Some suggestions for improving student performance in these areas are also provided. Teachers are encouraged to attend a College Board workshop to learn strategies for improving student performance in specific areas.

Question 1

What was the intent of this question?

This question assessed the students' understanding of a range of chemical concepts concerning the physical properties of ionic compounds. The students were asked to comment on a series of scenarios that dealt with a single ionic compound (LiCl), as well as compare/contrast the physical properties of different cations (Li^+ vs. Na^+) or ionic compounds (LiCl vs. NaCl). In part (a) students were presented with experimental calorimeter data, obtained from the dissolution of LiCl in water, and asked to calculate the magnitude of the heat flowing between the system and its surroundings. With the calculated value for heat energy, students were then asked to calculate the change in enthalpy of solution of LiCl (ΔH_{soln}) in units of kJ/mol_{rxn}. In part (b) students were asked to write out the complete electron configuration for sodium ion (Na^+). In part (c) students were asked to explain why the ionic radius of Na^+ is greater than that of Li^+. In part (d) students were asked to determine which salt, LiCl or NaCl, has the greater lattice enthalpy and to justify their selection. In part (e) students were provided a diagram of a typical three-dimensional lattice structure composed of small and large ions (represented as black and gray circles, respectively). Students were asked to label each type of circle with the correct ions, either Li^+ or Cl^-. In part (f) students were presented with a dissolution scenario that offered some information about the thermodynamic properties involved in such a physical change. The students were then asked to identify the particles that are primarily involved in the exothermic process of dissolution and to identify the primary type of interaction that occurs between the particles.

How well did students perform on this question?

The mean score for question 1 was 3.72 out of a possible 10 points. The score distribution approximately resembles a Gaussian curve, with a maximum of 15 percent of students earning 3 out of 10, 13 percent earning 2 out of 10, and 14 percent earning 4 out of 10. In general, the vast majority of all points were earned in parts (a)(i) and (e), and to a lesser extent part (b). The most challenging parts of the question were parts (c), (d), (a)(ii), and (f). In each of these parts, students were asked to communicate chemical concepts through the written word (some attempted to communicate through schematics and diagrams). Most students attempted question 1, with only 1 percent of the students not making an attempt.

What were common student errors or omissions?

Part (a):

- Students used the incorrect mass in the $q = mc\Delta T$ equation, choosing to use 100 g of water or 10 g of LiCl, rather than the 110 g of system (water + LiCl).
- Students also used the incorrect value for ΔT in their calculation. This error primarily arose from mistakenly using a single temperature or incorrectly calculating ΔT (calculating $T_i - T_f$).
- Reporting the incorrect set of units for the heat energy.
- The units of ΔH_{soln} that were provided in the stem confused students. The inclusion of kJ/mol$_{rxn}$ led students to attempt to solve for ΔH_{rxn} (ΔH_{soln}) with enthalpies of formation ($\Delta H^\circ_{rxn} = \Sigma\Delta H^\circ_f$ products $- \Sigma\Delta H^\circ_f$ reactants).
- Students did not recognize that ΔH_{soln} was in reference to the system and that, therefore, they had to change the sign for the value of the heat energy that they obtained in part (a)(i).
- Many students converted the energy from part (a)(i) to kJ and then inserted "mol^{-1}", rather than dividing energy by the moles of LiCl.

Part (b):

- Students provided the complete electron configuration for Na, and not Na^+, so the $1s^2\ 2s^2 2p^6\ 3s^1$ configuration was very common.
- Students also added an electron to the electron configuration for the Na^+; $1s^2\ 2s^2\ 2p^6\ 3s^2$.
- Students did not recall the "order of filling" electron sublevels and/or the maximum number of electrons allowed in a particular sublevel.
- Students used the noble gas configuration in place of the "complete" electron configuration.
- Many students did not know what an electron configuration was and offered orbital box diagrams or Bohr models instead.
- Use of subscripts was common, but did earn the point.

Part (c):

- Students chose to use periodic trends as the lone explanation for the difference in ionic radii.
- Students used general phrases, such as "more energy levels", "higher energy levels", "more energy shells", etc., to explain the sodium ion's larger radius.
- Students were confused about the meanings of, and when and how to apply, some of the key atomic structure terms, such as level, shell, sublevel, subshell, and orbital. For example, "sodium ion has electrons in more orbitals" or "sodium ion has a higher energy sublevel" would not earn the point.
- Students attempted to apply "shielding" as an explanation — "…outer level shielded from nucleus so less attracted" or "more shielding" or "less shielding".

Part (d):

- Predicting that LiCl has the larger lattice energy because Li^+ was smaller than Na^+ without referencing Coulomb's law.
- Predicting that LiCl has the larger lattice energy by stating or implying that LiCl had a smaller radius, without explicitly describing the shorter Li^+/Cl^- "bond" length, stronger "bond", or some physical description of the closer proximity of these two ions relative to Na^+ and Cl^-.

- Predicting that LiCl has the larger lattice energy by stating that smaller molecules pack together more tightly.
- Applying Coulomb's law to the ionization characteristics of lithium atoms/ions, sodium atoms/ions, or LiCl, and not to the electrostatic properties within a lattice structure.

Part (e):

- Students identified the larger ion (circle) as being lithium ion and the smaller black ions as chloride ions.
- Students did not include the charge on the ions (Li instead of Li^+).

Part (f):

- Maybe it is due to the units in part (a)(ii), but students attempted to answer this question by chemically reacting LiCl with water, rather than dissolving LiCl in water. Products such as Li_2O, H_2, and HCl were common.
- Students identified particles from the ionization of water (from the reaction with LiCl) interacting during the dissolution process. Ions included OH^-, H^+, O^-, and O^{2-} along with "negatively charged oxygen" and "positively charged hydrogen". Looking for "partially charged" or "negatively charged oxygen end of water" as descriptors.
- Diagrams of water frequently labeled O as "O^- or O^{2-}" and H as "H^+", as opposed to partially charged oxygen and hydrogen.
- Students provided unlabeled or incorrectly labeled diagrams to explain the interaction between the particles.
- Students didn't carefully read the whole question and omitted any mention of the type of particle-particle interaction associated with the exothermic process during dissolution.
- Students had a difficult time differentiating between the various types of intermolecular forces.
- Students misinterpreted the dissolution process as a chemical reaction between H_2O and LiCl, primarily producing Li_2O, HCl, LiOH, and H_2.
- Students described the endothermic breaking of LiCl bonds (dissociation of LiCl into Li^+ and Cl^-) as exothermic.
- Students assigned individual ions as possessing dipole moments.

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?

- Encourage/require the students to READ MORE material in addition to their textbook; articles about chemistry in the news, level-appropriate articles from *J. Chem. Educ.*, etc.
- Have students practice explaining trends contained within mathematical equations (e.g., Coulomb's Law). A periodic trend is an effect, not a cause.
- Require students to label diagrams clearly to improve communication with chemists/scientists from other high schools, colleges, and different areas of the country/world.
- Differentiate between shells, subshells, level, sublevels, and orbitals. They are not all necessarily interchangeable.
- Require students to show all work and report calculated values with the correct number of significant figures and units.
- Remind students to define all abbreviations the first time that they are used in a written assignment. Different scientific communities, educators, and laboratories use different abbreviations or acronyms to communicate a chemical concept or phenomenon.
- Differentiate between exothermic and endothermic processes/reactions.
- Differentiate between atoms, ions, and molecules.

Question 2

What was the intent of this question?

Question 2 explored students' knowledge of reaction types, stoichiometry, kinetics, thermodynamics, molecular structure in the form of Lewis diagrams, and net-ionic equations. In part (a) students were to identify the type of reaction that occurs when $NaHCO_3$ reacts with $HC_2H_3O_2$. In part (b) students were to identify the limiting reactant in the reaction and provide a calculation to justify the identification. In part (c) students were asked to take a macroscopic observation and explain the change in reaction rate in terms of reactant particle collisions. In part (d) students were to determine whether the reaction between $NaHCO_3$ and $HC_2H_3O_2$ is driven by enthalpy, entropy, or both enthalpy and entropy, and justify their selection in terms of $\Delta G°$. Students were given information in part (e) on the HCO_3^- ion and asked to draw a Lewis electron-dot diagram(s) consistent with the given information. Students were then to write a net-ionic equation for what happens when $HNO_3(aq)$ is added to eqimolar amounts of $HC_2H_3O_2$ and $NaC_2H_3O_2$.

How well did students perform on this question?

The mean score on question 2 was 4.39 out of a possible 10 points. Most students attempted all parts of the question and were able to earn points in one or more parts. Total scores were found at each step from 0 to 10 but there were relatively few perfect responses.

What were common student errors or omissions?

Since the question included many parts that probed students' understanding of concepts from across the entire curriculum, there were errors or omissions possible in every part.

Part (a), selecting and justifying a choice of reaction types, was accessible to students. Many were able to both correctly identify and provide justification for the type of reaction for 2 points. However, students who were able to identify correctly the type of reaction as acid-base were frequently unable to justify the answer by indicating that a proton transferred from an acid to a base or by identifying the acid and the base.

Part (b) was a 2-point limiting reactant question. Students earned the first point by calculating the number of moles of each reactant or by another acceptable calculation, such as grams of $NaHCO_3$ required. Students earned the second point by comparing their calculated values for moles to select the limiting reactant, using the stoichiometric 1:1 ratio from the balanced equation previously given in the prompt. Students could also make a calculation, converting each reactant to mass of one of the products. In cases where students miscalculated the number of moles, the point for stoichiometric comparison of the two reactants could still be earned with a comparison consistent with the incorrect values. A common mistake included the comparison of the mass of acetic acid, as calculated from its volume and molarity, to the original mass of the sodium hydrogen carbonate solid.

An understanding of the collision theory of chemical reactions was required for part (c). In this part, students were required to link a laboratory observation about the rate of bubble production with the collision theory of chemical reactions. The single point for the part was earned by describing that diminishing concentration of reactants (leading to fewer particles) caused less frequent collisions and therefore was associated with a slower rate (or fewer bubbles produced). A common mistake was not mentioning collisions at all. Some students explained the change of reaction rate, but did not connect it to collisions.

An understanding of the relationship between the thermodynamic factors $\Delta H°$, $\Delta S°$, and $\Delta G°$ was required for part (d). One point was earned for circling "entropy", the correct choice among choices of one or both of the thermodynamic factors which might drive the reaction forward. Once the factor "entropy" was chosen, another point could be earned by determining the signs or by describing the effects of all three thermodynamic factors ($\Delta H°$, $\Delta S°$, and $\Delta G°$) and explaining the relationship among them. Some students did not know what "drives the chemical reaction" meant but many of these students understood the Gibbs equation and indicated how the signs of $\Delta H°$ and $\Delta S°$ affected the value and sign of $\Delta G°$. A common mistake was to interpret "cooling" as meaning "exothermic reaction", which forced a negative sign to be assigned incorrectly to $\Delta H°$. Students who made this error and circled "both enthalpy and entropy" earned one point for consistency. Another common mistake involved misremembering the sign on $\Delta G°$ as positive for a thermodynamically favorable process. Those who made this error and circled "enthalpy only" also earned one point for consistency. Still another common mistake was to overlook the data provided and to simply say that, due to the Gibbs equation, $\Delta G°$ depends on both $\Delta H°$ and $\Delta S°$.

In part (e) students were required to showcase their mastery of Lewis structures and resonance. They earned one point by drawing a correct Lewis structure. The second point could be earned by indicating resonance forms or showing the delocalization of an electron pair over two adjacent carbon-oxygen bonds. A typical error showed resonance as a rotation of the ion rather than a change in the bonding. A common error of the Lewis structures was to leave out one or more of the lone pairs of electrons in the structure or to leave out the extra electron that gives the anion its charge. Another common error was to provide just a single Lewis structure when a minimum of two are required to show resonance.

Part (f) required students to write a net-ionic equation for one point. Less than one in five students earned this point. Once the conjugate base of the buffer, acetate, was identified, students were required to generate a net-ionic equation indicating the reaction of the hydronium cation of the strong acid with the weak base acetate to form the weak acid acetic acid. Students were frequently unable to identify the acetate anion as the part of a buffer that might interact with the strong acid (nitric acid). Another common mistake was for students to include the entire buffer in their net-ionic equations. In addition, some chose to write the net-ionic equation of the original acid-base reaction. The skill of writing net-ionic equations is still a requirement of the AP Chemistry curriculum and students should be able to demonstrate an understanding of this skill.

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

Students should read the directions carefully and follow them. The general directions to the free-response section of the exam indicate that all work must be shown for calculations, but too often this directive was disregarded. Students should be reminded that work shown can earn partial credit. Sometimes simple directions like "in the box below, draw…" or "circle one of…" were ignored. Statements leading students to a specific topic area should be read and observed. For example, if the question states "justify your selection in terms of $\Delta G°$", then students should include $\Delta G°$ prominently in their answers. If "explain…in terms of the collisions" is given as a prompt, then "collisions" should be mentioned in the answer.

Question 3

What was the intent of this question?

Question 3 evaluated students' ability to analyze data from a common laboratory experiment. Students were given pictures of the experimental steps to synthesize and collect the ionic solid, MI_2. In part (a) students calculated the moles of I_2 that reacted with an excess of metal M. In part (b) the value from part (a) was used to calculate the molar mass of the metal M. In part (c) students proposed an experimental test that could be used to determine if MI_2 is an ionic solid, and then explained how the results of the test supported this claim. Students explained why I_2 is solid at room temperature, but Br_2 is a liquid in part (d). In part (e) students utilized a standard reduction potential chart to choose which species, H_2O_2, $Na_2S_2O_3$ or $Na_2S_4O_6$ could reduce the leftover I_2, and then to justify their claim. Students wrote the net-ionic equation for the reaction between I_2 and the solution they chose in part (e).

How well did students perform on this question?

The mean score was 3.83 out of a possible 10 points.

What were common student errors or omissions?

Part (a): *Given that metal M is in excess, calculate the number of moles of* I_2. [1 point]

In general this point was accessible to the majority of students. They earned one point for the correct calculation of the moles of I_2. The most common error/misconception is that students used the molar mass of an iodine atom, 127 g/mol, to calculate the moles of I_2, resulting in an answer that is twice the correct answer.

Part (b): *Calculate the molar mass of the unknown metal M*. [2 points]

Most students were able to earn at least one of two points on part (b). Many had difficulty determining the mass of M used in the reaction and assumed that all the metal was used up. They calculated the mass to be 1.092 g instead of 0.263 g. More students were able to earn the second point if they correctly calculated the molar mass using their mass of the metal.

Other common errors or omissions included:

- Dividing the number of moles from part (a) (which were moles of I_2) by 2 to get the number of moles of M.

Part (c): *Propose an experimental test the student could perform that could be used to support the hypothesis. Explain how the results of the test would support the hypothesis if the substance was ionic.* [2 points]

Students earned two points for providing an appropriate test and explaining how the results support the hypothesis. Many had difficulty distinguishing between an experimental test and ionic property. Examples of this included, test if MI_2 is made of a metal and a nonmetal; or see if the compound transfers electrons from one atom to another.

Other common errors or omissions included:

- Stating that only (or all) ionic compounds dissolve in water
- Proposing ionic solids conduct electricity
- Suggesting that ionic compounds will be attracted to a magnet since they are made of a metal and nonmetal
- Only providing the experimental test but not the evidence for why MI_2 is ionic

Part (d): *Explain why* I_2 *is a solid at room temperature whereas* Br_2 *is a liquid. Your explanation should clearly reference the types and relative strengths of the intermolecular forces present in each substance.* [2 points]

Students earned two points for identifying the forces in each substance as London dispersion forces and for explaining why the forces are stronger in I_2 than Br_2. In many cases, students earned only one point due to missing IMFs or explanation.

Other common errors or omissions included:

- Stating that I_2 has dipole-dipole interactions and Br_2 has London forces
- Only describing the forces in Br_2 or I_2 but not both

- Saying I_2 has larger London forces due to a larger mass
  - Confusing intermolecular and intramolecular forces

Part (e): *Which solution should the student add to $I_2(s)$ to reduce it to $I^-(aq)$. Justify your answer, including a calculation of $E°$ for the overall reaction.* [2 points]

One point was earned for circling $Na_2S_2O_3$ and the second point for calculating a cell voltage of 0.46 V and explaining that a positive voltage indicated that the reaction was thermodynamically favored. Even students who chose the $Na_2S_2O_3$ and calculated the voltage would often forget to explain why this was the correct choice.

Other common errors and omissions included:
  - Confusing what species will be the reactant and product in the half reaction
  - Switching the sign for a $E°$ or ΔG for a thermodynamically favored reaction
  - Failing to switch the sign of the reduction potential when calculating $E°$ for the reaction

Part (f)*:* *Write the balanced net-ionic equation for the reaction between I_2 and the solution you selected in part (e)*. [1 point]

This part earned one point for the correctly balanced equation that was consistent with the circled answer in part (e).

Other common errors and omissions included:
  - Not balancing mass and charge
  - Writing equations that are not consistent with part (e)
  - Leaving electrons in the final equation
- Including Na^+ in the 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?

- Encourage students to review their answers to make sure their response answers the question.
- Conduct laboratory experiments with your students so students are familiar with reading data tables and experimental design.
- Emphasize the importance of showing your work for all calculations with proper units. Credit was not earned for the cell voltage, $E°$, when work was not shown.
- Stress the proper sign notations for $E°$ and ΔG for a thermodynamically favored reaction.
- Teach students the strength of London dispersion forces are dependent the polarizability of the electron cloud, not the molar mass of the substance.
- Practice writing net-ionic equations.
- Remind students that a justification usually requires a written explanation along with a numerical calculation.

Question 4

What was the intent of this question?

Question 4 explored students' knowledge of weak acid equilibrium conditions in aqueous solution and conjugate acid/base relationships in a buffered solution. Students were given two scenarios involving solutions of phenol, C_6H_5OH (*aq*). In part (a) students were to calculate the pH of a 0.75 M solution of phenol given the K_a value for this weak acid. In part (b) students were asked to select pH values of a buffered solution that would ensure more than 50 percent of the phenol was in its deprotonated form, $C_6H_5O^-$(*aq*).

How well did students perform on this question?

On question 4, the mean score was 1.35 out of a possible 4 points. Students attempted to answer both parts of the question in the majority of cases, and more points were earned in part (a) than in part (b).

What were common student errors or omissions?

In part (a):

Student errors frequently included:

- Misapplication of the Henderson-Hasselbalch equation to a solution that is not a buffer system.
- Assuming that phenol was a strong acid that would completely ionize in aqueous solution.
- While many used it correctly, some students who used an ICE table to set up the equilibrium concentrations of the weak acid system would still calculate the pH using an unrelated method, suggesting that they were treating the table as an algorithmic exercise, rather than understanding the underlying chemical principles.
- Students frequently rounded intermediate answers during the calculation process. Since the calculation process for part (a) involves taking a square root and a logarithm, the effects of such rounding errors are compounded.

In part (b):

Typical errors involved conceptual misunderstandings regarding buffer systems. These included:

- Determining that 50 percent dissociation corresponded to a 1:2 ratio, rather than a 1:1 ratio, between conjugate base and acid. Other students indicated that the hydronium ion and conjugate base concentrations, rather than conjugate acid and base concentrations, were equal at 50 percent dissociation.
- Using an incorrect sign in the Henderson-Hasselbalch equation, leading to the conclusion that conjugate base concentration would increase for *decreasing* buffer pH. This error further suggests that students are considering the problem algorithmically, rather than thinking about the chemical system.
- Surmising that an upper limit of some kind, based on concentration of conjugate base, or another, more arbitrary criterion, would prohibit the formation of a buffer with a pH greater than 12 or 13. These types of errors were often associated with the student conflating the concepts of a buffer system and a weak acid-strong base titration. This misconception was frequently revealed when students attempted to compare the "1/2 equivalence point" to the "equivalence point", terms that are more appropriately used in titration applications, not buffer systems.

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?

Concerning weak acid equilibrium:

Students should understand that the Henderson-Hasselbalch equation applies to finding the pH of a buffer system, and is not appropriately used in determining the pH of a weak acid (not in a buffer system). Students should consider the equilibrium of the weak acid system, rather than using the Henderson-Hasselbalch equation as a "black-box" algorithm.

Similarly, the ICE table method should be discussed as a way to examine changes that occur as equilibrium is established, rather than as an algorithmic exercise.

Students should be comfortable with using approximation methods (i.e., the "5 percent rule") and avoid the use of a quadratic equation when working with weak acids. Avoiding the approximation and insisting on using the quadratic is a further symptom of students who treat the problem algorithmically rather than chemically.

Concerning buffer systems:

In this question, students are asked about the possible pH values of a buffer system that would result in a conjugate base concentration greater than 50 percent. This is qualitatively different than the examination of a titration curve as it proceeds through "the buffer region". However, exam results indicate that students frequently confuse one for the other. In extreme cases, students would sketch a titration curve, attempting to show how the pH of the system was changing during the "process".

The titration misconception also revealed that many students treat the pH scale as a linear, not a logarithmic, scale. For example, such students do not recognize that the difference between pH 10 and pH 5 is a 100,000 factor increase in $[H^+]$.

Students should recognize that a 50 percent deprotonated weak acid will have a base to acid ratio of 1:1, not 1:2. The concentration of acid is frequently misinterpreted as "amount of overall species" in this context.

General considerations:

The general terms "acidic solution" referring to $pH < 7$ and "basic solution" referring to $pH > 7$ are only valid when comparing the solution's pH to that of pure water. These terms seem to confuse many students, so that the students do not consider the relative concentrations of the specific conjugate acid and base in the question. Perhaps the usefulness of these terms should be reconsidered. Likewise, pH has no theoretical limits — it may be lower than 1 or higher than 14.

Students should not round intermediate answers when performing multi-step calculations. Errors are frequently compounded when this happens. Similarly, students need to show all their work when performing calculations. Partial credit is difficult to earn when work is not shown. Likewise, numbers in exponential notation should be written with the exponent, and not in a truncated form.

Students should read questions carefully, as one part of the question may not be relevant to another part of the question. Many errors in part (b) appear due to students believing that the answer in (a) is relevant to their work in (b), which it is not in this case.

Question 5

What was the intent of this question?

Question 5 assessed students' understanding of the ideal gas law, kinetics and reaction-order, and the ability to interpret real experimental data and patterns from graphs. In part (a) students were asked to determine the initial concentration of the gas C_4H_6 for trial 1 from a graph of kinetic data for concentration versus time, and then use this value to determine the initial pressure of C_4H_6 for trial 1. In part (b) the students had to examine three different graphical representations of the same data – $[C_4H_6]$ vs time, ln $[C_4H_6]$ vs time, and $1/[C_4H_6]$ – and determine the order of the reaction with respect to C_4H_6. In part (c) students were asked to calculate the rate constant k from the given initial rate of the reaction for trial 1.

How well did students perform on this question?

Question 5 was worth four points and the mean of the question was 2.08. The most commonly earned points were in part(b) for the identification of the reaction as second order and in part (a) for setting up a $P = nRT/V$ equation.

What were common student errors or omissions?

Part (a):

- Students frequently did not relate n/V to a concentration given in the graphical data. The problem did not specify a volume because none was necessary given the graphical data was in concentration (mol/L), although many students assumed an arbitrary volume to complete the calculation. However, many students did not connect the graphs with the variables n and V in the ideal gas law. Many students apparently substituted the reactant coefficient, 2, for n and assumed 1 L for V. Some students substituted the molar mass of C_4H_6 for n or used the molar mass in a calculation in an unnecessary conversion. A significant number of students indicated a misconception of concentration by indicating no V was given.

- Other students misread the graphical data, either choosing the initial concentration for trial 2 (instead of trial 1) or demonstrating a misconception of the term "initial" by choosing the concentration as $t = 1$ s (instead of $t = 0$ s).

- A smaller but significant number of students substituted the wrong gas constant, R, with the wrong units (8.314 J/(mol K)) instead of 0.08206 L atm/(mol K).

- Additionally, transcription errors such as 0.02 mol/L substituted into $P = nRT/V$ as 0.2 or 2.0 were common. Arithmetic and algebraic errors were also common.

Part (b):

- Students were asked to look at three graphs and identify the reaction as second order with respect to the concentration of butadiene. Answers given included 0, ½, 1, 2, 3, and 4.

- Students generally did well at indicating the reaction as second order with respect to C_4H_6. However, since no explanation was required it is uncertain how many determined this correctly from the graphical data and how many stated this because of the reaction coefficient.

- The most common wrong answer was "first order," but as no explanation was required the reason cannot be surmised. Other students indicated that the first graph referred to a zero-order reaction, the second graph referred to a first-order reaction and the third graph referred to a second-order reaction, but did not choose the order with respect to C_4H_6.

- A smaller but significant number of students indicated that, because the third graph was linear, the reaction was third-order with respect to C_4H_6.

Part (c):

- The most common errors in this calculation were mathematical. Many students used correct expressions but had incorrect answers, indicating arithmetic errors, and students solved the rate law equation or the integrated rate equation algebraically incorrectly for k. A common error was the failure to square the concentration in a second order rate law, rate = $k[C_4H_6]^2$.

- Many students substituted incorrectly into the chosen rate constant expression, choosing incorrect values from the graphs (ignoring axis labels) or substituting the initial rate for the initial concentration.

- A smaller but significant number of students indicated a misconception about the difference between k, the rate constant, and K_{eq}, the equilibrium constant. Some students also misidentified t, time, as T, temperature.

- Some students attempted to determine k, the rate constant, using the second-order integrated rate law based on a one to one reaction stoichiometry (A → P). However, because butadiene gas reacts with a two to one reaction stoichiometry (2 A → P), the second-order integrated rate law for this system (2 A → P) is:

  $$\frac{1}{[\mathrm{A}]_t} = 2kt + \frac{1}{[\mathrm{A}]_o}$$

  The slope of the graph for 1/[A] vs. time for the 2 A → P system is $2k$ ($m = 2k$), where $k = m/2$.

  Since the reaction equation is $2\ C_4H_6 \rightarrow C_8H_{12}$, the relative rate of disappearance of C_4H_6 is twice the rate of reaction. Students therefore should divide the slope of the graph 1/[A] vs. time by 2, since the data on the graph represent the molecules of butadiene undergoing a reaction. The value of the rate constant determined using this method is 2.5, consistent with the rate constant determined using the differential rate law, Rate = $k[C_4H_6]^2$. Students who calculated k using the second order integrated rate law expression for A → P, where $m = k$, still earned 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?

General considerations:

Some students did not follow the directions that were stated in the question. The recommendation is to require students to follow directions, read the prompt carefully, and answer the question asked. If no justification is required, do not write a justification. To earn points, students need to show work. Students who showed their work and displayed units with their numerical values in parts (a) and (c) benefited by being able to see the units cancel, leaving correct units for the answer.

For part (a) many students would have done better on the calculation of the initial pressure of butadiene if they had included units with the values of n, V, R, and T in their calculation. The recommendation is to require students to use units in all calculations and show the cancellation of units to make sure the end units are the desired units.

Many students used $R = 8.314$ J/(mol K) in the ideal gas law equation $PV = nRT$ instead of $R = 0.08206$ L atm/(mol K). Teachers should have their students practice solving $PV = nRT$ problems using the correct term for "R" the universal gas constant in order to have units of "atmospheres" for pressure. The recommendation is to require students to include units with all numbers in their intermediate steps.

Be sure students know how to use their calculators for exponential functions (such as to square the initial concentration in the differential rate law equation).

Concerning kinetics:

Students need to be reminded that for any data, one can create the set of graphs concentration vs. time, ln(concentration) vs. time, and 1/(concentration) vs. time. The graph that yields a straight line indicates the order of the reaction. Students need to see all three graphs for each reaction order.

Concerning the Ideal Gas Law:

Students need to realize that the n/V term (in $P = nRT/V$) can be interpreted as a molar concentration. Gas concentrations can also be expressed in terms of molarity.

Concerning graphs:

Have students do at least two kinetics laboratory experiments in which the students gain experience collecting data for a first-order and a second-order kinetics system and analyzing the data. Students need to understand there is a connection between the dots on the graph and the recorded experimental data, ideally by recording and plotting their own data. Having technology is fine but students often miss what the data are indicating when the work is done for them.

Students need to practice reading graph axes. The plots indicate both numerical values and units. In a plot of 1/[A] vs. t, the vertical axis indicates units of L/mol and the dots represent the inverse has already been taken. For example, when [C_4H_6] is 0.020 mol/L, the point at (0, 50) on the 1/[C_4H_6] vs. t graph represents 1/0.020. Students do not need to take the inverse of the inverse when calculating the slope.

Students need to know the "initial" time point is at $t = 0$ and not at $t = 1$.

Students need to be able to correctly calculate the slope of a line from data on a graph. Students must be taught that the proper way to calculate a slope of a line is to draw the best straight line through the experimental data points (or use their calculator's Method of Least Squares program) and use points on the line and NOT to use experimental data points (which contain error).

Require students to be accurate in transcription. Students need to accurately read and learn how to transfer values from a graph, i.e., "0.020 mol/L" for the initial concentration of butadiene is not the same as "0.20" or "0.0020". Have graphs where students have to determine data points when there is more than one trial plotted on the same graph.

Question 6

What was the intent of this question?

Question 6 explored students' understanding of the equilibrium of an ionic system. Students were given an equilibrium reaction forming $Ba(EDTA)^{2-}(aq)$ from $Ba^{2+}(aq)$ and $EDTA^{4-}(aq)$. In part (a) after considering the value of K, students were asked to calculate the concentration of $Ba(EDTA)^{2-}(aq)$ after mixing 50 mL of 0.30 M $EDTA^{4-}(aq)$ and 50 mL of 0.20 M $Ba(NO_3)_2(aq)$. In part (b) students were asked to determine what would happen to the number of moles of $Ba^{2+}(aq)$ after the solution from part (a) was diluted to 1.00 L.

How well did students perform on this question?

The mean score for question 6 was 0.45 out of possible 4 points. In general, this was a challenging question. Students scored slightly better on part (a) than on part (b), but most students did not earn points on either part. Most students attempted question 6 (only 8 percent of the students omitted the question).

What were common student errors or omissions?

Part (a):

- Students used the initial concentrations of the aqueous reactant before mixing them in their calculations.
- Students did not understand that the large K meant that the reaction went to completion, and treated this as a standard equilibrium problem. Students then decided that x (the change in reactant concentrations and the concentration of $Ba(EDTA)^{2-}(aq)$) was not significant.
- Students did not recognize the limiting reactant.
- Students had difficulty solving the quadratic equation when treating it as a standard equilibrium question.
- Students appeared confused by the use of $EDTA^{4-}$ and the complex ion $Ba(EDTA)^{2-}$.

Part (b):

- The most common answer in part (b) was "equal to", using a conservation of mass justification.
- Students did not recognize that the concentrations of all species are affected by dilution.
- In solving for Q, when students divided 0.1 by 0.01, they calculated $Q = 1/10\ K$ and therefore suggested the $[Ba^{2+}(aq)]$ would be less after dilution.
- Students used Le Chatelier's Principle as the sole reason for a change in $[Ba^{2+}(aq)]$.
- Making water a reactant or product in the reaction.
- Students answered in terms of the concentration of Ba^{2+} rather than the number of moles of Ba^{2+}.

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?

- Use examples of reactions with large K values when discussing equilibrium (e.g., strong acids, very soluble solutes, etc.).
- Use "real life" examples of reactions in discussions. Many students were confused by the EDTA.
- Work to help students understand that Le Chatelier's principle describes observations of equilibrium reactions, but does not cause changes.
- Have students evaluate the feasibility of numbers calculated (e.g., 1.2×10^6 M is very high!)
- Encourage students to show their work for calculations.

Question 7

What was the intent of this question?

Question 7 evaluated students' ability to collect data and utilize that data in a common laboratory calculation. In part (a) students were asked to determine the volume of the sodium hydroxide solution that was delivered to the flask, given two images showing the same buret at initial and final levels, during a titration experiment. The solution levels in the buret were enlarged to aid data collection by the student. In part (b) students were asked to use the volume from part (a) to determine the molarity of the unknown acid solution. In part (c) an error was described in which too much base was accidentally delivered into the flask. The students were asked to determine if this error would increase, decrease, or have no effect on the calculated molarity of the acid, and to justify their choice.

How well did students perform on this question?

The mean score for question 7 was 1.76 out of a possible 4 points. In part (a) students often had trouble reading the buret correctly to determine the volume of base added to the flask. In general, students did well in part (b), calculating the molarity of the unknown acid. Most students used the $M_aV_a = M_bV_b$ approach to solve for the molarity. Some students used a stoichiometric approach. Both strategies earned the point if completed correctly. In part (c) students correctly answered the conceptual question about the effect of the volume error on the calculated acid concentration. The justification point for part (c) was difficult for many students to earn. Many students correctly used a mathematical approach for the justification, with many substituting in a larger base volume than used in part (b). Other students used a narrative to justify their answer to the question.

What were common student errors or omissions?

Part (a)

- Students often did not give the volume with four significant digits and two decimal places.
- Buret readings were given with only one decimal place.
- The delivered volume was given with only one decimal place, sometimes when the burets were read to two decimal places.
- Students did not know how to read a buret. Some students made the buret readings at the top of the meniscus. Some students read the buret from the bottom to the top. Some students subtracted each reading from 50.00 mL and then solved for the delivered volume, which could result in the correct answer. Students used the final buret reading of 37.30 mL as the delivered volume.

Part (b).

- Students sometimes switched the volumes of the NaOH solution and the unknown acid solution in their molarity calculation.
- Students seemed to be confused with a dilution calculation and used the sum of the solution volumes to incorrectly determine the concentration of the acid solution using $M_1V_1 = M_2V_2$.
- Students sometimes thought that calculating moles is the same as calculating the molarity.
- Some students attempted a dimensional analysis approach, but put both volumes in the numerator (or denominator).

Part (c).

- Some students stated that the error was increased and did not indicate the effect of the error on the calculated acid concentration.

- Many students simply restated the prompt.
- Students did not clearly communicate that the calculated number of moles of base would be increased and/or relate this to the calculated acid concentration. Often students said “more base” without clearly stating what was meant by the phrase.
- Students would sometimes seem to confuse the volume of the base with the concentration of the base. These students would incorrectly state that the concentration of the base increased while the prompt stated that the volume of the base had increased.
- Some students misunderstood titration and incorrectly stated that calculated acid concentration is decreased in the solution by the reaction with the excess OH^-.
- Some students thought that the increased volume in the flask decreased acid concentration by dilution.
- Some students stated that excess OH^- increased the pH, therefore the calculated concentration of the acid solution was decreased.
- Some students described the “equilibrium” and tried to invoke Le Chatelier’s principle.

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?

Part (a).

- Make sure that students have experience using a buret.

Part (b)

- Students need practice calculating solution concentrations.
- Make sure students can use stoichiometry to perform titration calculations rather than relying on $M_aV_a = M_bV_b$, which only applies to a 1:1 stoichiometric acid to base ratio.

Part (c)

- Provide students with opportunities to justify and explain their conceptual understanding of laboratory procedures.