Chief Reader Report on Student Responses:

2017 AP® Chemistry Free-Response Questions

• Number of Students Scored	158,931			
• Number of Readers	347			
• Score Distribution	Exam Score	N	%At	
	5	15,985	10.1	
	4	25,760	16.2	
	3	41,524	26.1	
	2	41,674	26.2	
	1	33,988	21.4	
• Global Mean	2.67			

The following comments on the 2017 free-response questions for AP® Chemistry were written by the Chief Reader, Roger Kugel, 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 preparation 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   **Topics:** Gas laws, stoichiometry, kinetic molecular theory, Lewis diagrams, intermolecular forces
     Max. Points: 10   **Mean Score:** 5.47 ± 2.50

What were students expected to demonstrate in their responses to this question?

In order to answer this question, students were expected to draw on their knowledge and skills from a number of topic areas in the AP Chemistry curriculum. Some of the topics might have been taught initially in the first-year chemistry course. This question was a good example of the cumulative nature of chemistry. Students who retained the knowledge of topics presented over the span of their time in chemistry, as well as maintained the skills acquired in order to manipulate that knowledge in solving problems, had a decided advantage in presenting answers to the questions.

In this question the Learning Objectives (LO) assessed were 2.6, 2.13, 2.16, 2.21, 3.3, and 4.5. The Science Practices (SP) assessed were 1.4, 2.2, 2.3, 5.1, 6.2, and 6.4.

Part (a)(i) of the question dealt with simple stoichiometry of gaseous reactants. Students were required to use the Ideal Gas Law to apply relationships between macroscopic variables for a gas to calculate the number of moles of a gaseous reactant. Following the calculation of the number of moles of Cl_2 in the container, students were expected to display stoichiometry skills to calculate the number of grams of CS_2 required to react with all of the Cl_2. Part (b) of the question assessed student knowledge of Kinetic Molecular Theory as applied to gases. In part (b)(i) students were required to explain the results of an experiment where a change in the temperature affected the rate of the reaction relative to collision theory. The students were asked in part (b)(ii) to explain, using graphical techniques, how differences in the number and energetic quality of collisions led to some of those collisions being favorable, leading to a conversion of reactants to products.

Part (c) required students to display their knowledge of Lewis structures. In part (c)(i) students had to place electrons as bonding and nonbonding pairs around a skeleton structure provided in the prompt. Then the students had to refer to their drawings to predict two bond angles in the structure, using their knowledge of the number and type of pairs around the central atom, to lead them to an appropriate bond angle. Part (d) assessed students' knowledge of bond and molecular polarity and how that polarity might affect the types of intermolecular attractions and repulsions that might result. Part (d)(i) asked specifically about intermolecular forces between polar HCl molecules and part (d)(ii) asked students to predict the relative strengths of intermolecular forces by comparing two different types of molecules, using data about relative condensation points.

How well did the students address the course content related to this question? How well did the responses integrate the skills required on this question?

The mean score on Question 1 was 5.47 ± 2.50 points out of 10 points. The distribution of scores on Question 1 is shown below:
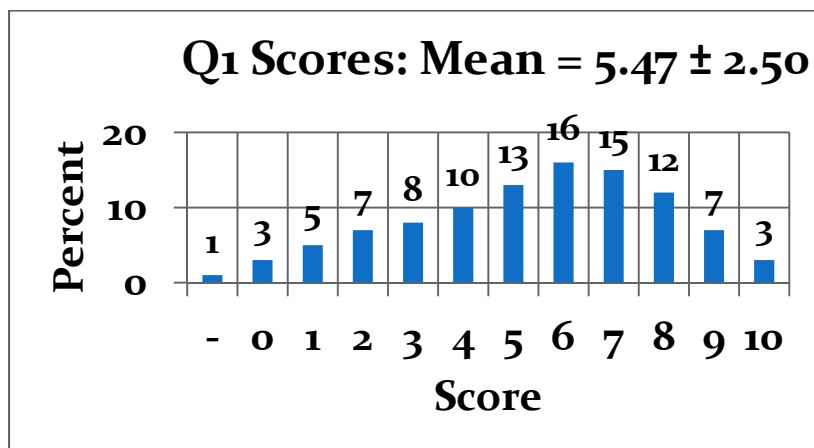
Most students were able to generate several points by using skills learned and concepts gained over two years of studying chemistry. Part (bi) proved to be a difficult point to earn, as students had to refer to both of two aspects (particles with great kinetic energy at the higher temperature AND collisions with sufficient force to overcome activation energy) to earn a point. Another difficult section was part (dii), where students had to make a counterintuitive decision about the relative strength of intermolecular forces to explain why nonpolar CCl_4 molecules have greater IMFs than those between polar HCl molecules.

What common student misconceptions or gaps in knowledge were seen in the responses to this question?

Common Misconceptions/Knowledge Gaps	Responses that Demonstrate Understanding
Part (ai): Choosing R with pressure units to match data Incorrect algebra: "n = RT/PV" Incorrect conversion of °C to K (or not converting at all!) Converting volume to 25,000 L (pay attention to units) Using ratio 22.4 L = 1 mol	0.40 *atm* so R = 0.08206 (L *atm*) / (mol K) $n = \dfrac{PV}{RT}$ 120°C + 273 = 393 K 25.0 L = 25.0 L Misconception; not at STP
Part (aii): Not showing work Not connecting answer from (ai) to (aii) Using coefficients of balanced equation as actual quantity of reactants in container Incorrect molar mass Ignoring balanced equation and using 1:1 ratio of reactants Inversion of mole ratio Use of 1:3 as mass:mass ratio	Follow directions Coefficients of balanced chemical equations contain information regarding the proportionality of the amounts of substances involved in the reaction. Calculation errors

Part (bi):	
Failure to answer prompt: how does ↑T affect collisions between molecules?	At the higher temperature the particles have a greater average kinetic energy than at the lower temperature.
Indicating only more collisions without saying more energetic particles	There are more collisions with sufficient force between particles with greater kinetic energy.
Not enough use of the comparative "more"	More energy to overcome the activation energy and more collisions.
Belief that no collisions occur until 120ºC is reached	At 120ºC reaction is observed to occur; no significant reaction is observed to occur at 30ºC but collisions do not stop.
Invoking thermodynamics	ΔG, ΔH, and ΔS not mentioned
Reference to a catalyst (temperature as a catalyst?)	No catalyst mentioned and temperature is not a catalyst
Focus on either increase in KE, speed, and force of collisions, or increased frequency of collisions but not both	See above
Part (bii):	
Most students lowered the entire curve, maintaining the shape	The 30º curve has a peak above and to the left of the 120º curve
Some kept the initial curve at the same height as the original curve	See above
Changing the position of the activation energy line	Changing temperature does not change the activation energy
Too many students merge curves at E_a line	30º curve is below the 120º curve in the region beyond the activation energy
Driving line into or below x-axis	
Not understanding that the area under each curve should be the same	
Once lower-temperature curve drops below original-temperature curve, it must stay below	

Part (ci):	
Incorrect number of valence electrons (should be 26)	2(6) + 2(7) = 26 valence electrons to place
Not obeying octet rule so wrong total number of electrons used	See above
Too many multiple bonds	Using multiple bonds only when the octet rule is insufficient for completing a correct Lewis structure
Follow octet rule first so expanded octets or multiple bonds are not required	See above
Lewis dot atoms drawn unconnected to each other	Review bonding
Lone pairs not included, only bonds	Review Lewis structures
Part (cii):	
Appearance of Lewis structure is not the geometry (that is, symbols in a straight line on the page does not mean 180° bond angle)	Total e^- pair = bonding pair e^- + nonbonding pair
Not counting number of electron domains around central atom before predicting bond angle	
Saying each bond has an angle, rather than relative positions of nuclei	
Stating a molecular geometry, rather than a bond angle	
Part (di):	
Ineligible terms include van der Waals; hydrogen bond; ion-dipole; covalent, ionic, or metallic bond	Intermolecular forces present in HCl(l) include dipole-dipole forces and London dispersion forces.
Failure to include London dispersion forces	
Confusing "intermolecular force" with "intramolecular force"	
Thinking HCl (g) or HCl (l) is an acid that is ionizing	

Part (dii):	
Argument that dipole-dipole interactions are stronger than London dispersion forces, so HCl must have higher boiling point that CCl_4	The intermolecular forces among CCl_4 molecules must be <u>stronger</u> than those among HCl molecules because the CCl_4 condenses at a higher temperature than HCl.
Failure to use data given	
Thinking that a higher condensation point must mean a lower boiling point	Actually same temperature
Mistaking "intermolecular forces" for "intramolecular forces"	
Mixing up "high" versus "low" temperature even when explanation is correct	
Comparing LDFs based on size/mass of atom rather than number of electrons and polarizability	
Students should practice determining differences between substances based on experimental physical properties	

Based on your experience at the AP® Reading with student responses, what advice would you offer to teachers to help them improve the student performance on the exam?

1. Have students do drills on algebra skills and encourage them to show all work in calculations, even if it seems obvious.
2. Remind students to read problems carefully and to answer the question posed.
3. Have students describe in their own words what happens to the distribution of molecular collision energies as T increases. (Lower T produces more collisions of lower energy—a higher M-B peak closer to zero energy).
4. Have students practice drawing Lewis dot diagrams and describing molecular shapes and polarities.
5. Have students describe in their own words why higher BPs MUST mean stronger IMFs.

What resources would you recommend to teachers to better prepare their students for the content and skill(s) required on this question?

- There are four years' worth of AP Chemistry free response questions and the associated scoring guidelines on the AP Chemistry exam page: https://apcentral.collegeboard.org/courses/ap-chemistry/exam?course=ap-chemistry
- Teachers could review elements of Q5 and Q6 from the 2014 exam, Q2 from the 2015 exam, and Q5 from the 2016 exam with their students.

Question #2   **Topic:** Lewis diagrams, formal charge, bond enthalpy, thermodynamic favorability, kinetic data analysis
Max. Points: 10   **Mean Score:** 3.15 ± 2.41

### *What were students expected to demonstrate in their response to this question?*

In parts (a) through (f) this question assessed students' understanding of several fundamental concepts: formal charge, determination of $\Delta H°$ and $\Delta S°$ of a reaction, and the relationships between concentrations, thermodynamic favorability, and K. In parts (e) and (f) the questions focused on the evaluation of data for a first-order reaction: the decomposition of urea.

In this question the Learning Objectives (LO) assessed were 2.21, 4.1, 4.2, 4.3, 5.8, 5.12, and 5.13. The Science Practices (SP) assessed were 1.4, 2.2, 2.3, 4.2, 5.1, 6.4, 7.1, and 7.2.

In part (a) students were asked to explain why one resonance structure of fulminic acid was better using formal charges. In part (b) students were asked to determine ΔH°_{rxn} for the conversion of fulminic acid (HCNO) to isocyanic acid (HNCO) using the given bond enthalpies. In part (c) students were asked to explain why $\Delta S°$ would be close to zero for the conversion of HCNO(g) to HNCO(g). In part (d) using their answers to parts (b) and (c), students were asked to choose which species would be present in higher concentration at equilibrium and to justify their choice in terms of thermodynamic favorability and the equilibrium constant. In part (e)(i) using a data table and graph of [CO(NH$_2$)$_2$] vs. time, students were asked to explain how the data supported a first-order rate law for the decomposition of urea. In part (e)(ii) using the proposed rate law and the data, students were asked to calculate the rate constant for the decomposition of urea. In part (f) given the information that the decomposition reaction was run at pH 13, students were asked to describe an experiment that would determine whether the reaction rate depended upon the concentration of OH$^-$.

How well did the students address the course content related to this question? How well did the responses integrate the skills required on this question?

The mean score for Question 2 was 3.15 ± 2.41 out of possible 10 points. The distribution of points on Question 2 is shown below:
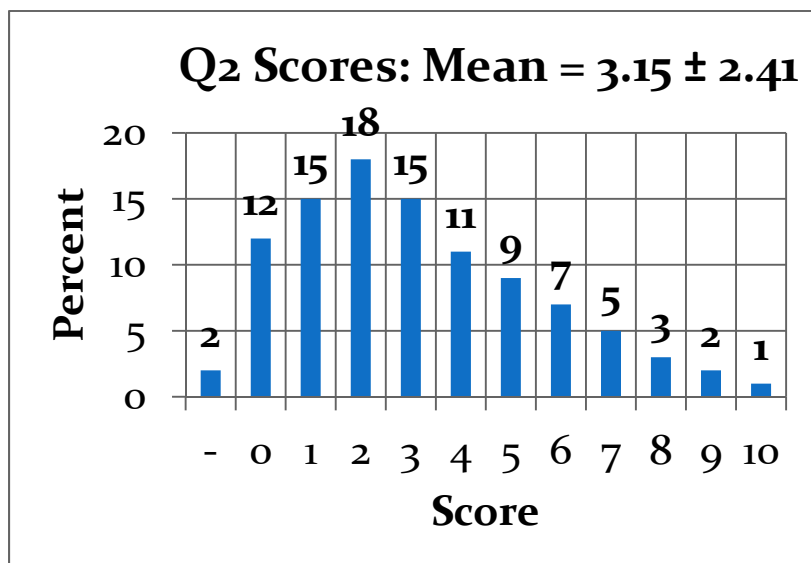
In general, this was a challenging question. Parts (a) and (d) were each worth 2 points and seemed to cause the most difficulty. Each required students to use fairly high level thinking. Part (a) asked students to make the connection between formal charge and electronegativity in determining which one is the better resonance structure. Part (d) required students to integrate concepts and relate thermodynamic favorability with $\Delta H°$, $\Delta S°$, and the equilibrium constant K in determining which species would be present in higher concentration. Parts (ei) and (eii) also caused some difficulty. Many responses were unable to recognize that the kinetic data indicated a constant half-life and had difficulties calculating and determining

appropriate units for the rate constant k. Parts (b), (c) and (f) contained the most accessible points in the question. Although many students used $\Delta H°_{products} - \Delta H°_{reactants}$ and incorrectly calculated a positive $\Delta H°_{rxn}$, most students were able to get the magnitude (246) correct. In part (c), most students recognized that without a phase change or change in number of molecules, the entropy change would be very small. In part (f), many students were able to describe an experiment involving changing pH or [OH−], gathering data and comparing to the data from the reaction run at pH 13. Most students attempted Question 2 (only two percent of the students omitted the question).

What common student misconceptions or gaps in knowledge were seen in the responses to this question?

Common Misconceptions/Knowledge Gaps	Responses that Demonstrate Understanding
Part (a): Students did not calculate/assign formal charges and/or attempted a justification without using formal charge. Students equated formal charges with the overall charge on the molecule. Students answered that the best structure has the charges on the outside, with lower charges in the "central" atoms Students did not compare both the oxygen formal charge and the carbon formal charge on each diagram. Students compared electronegativities of oxygen and nitrogen in the same diagram.	In the diagram on the left, the C atom has a formal charge of zero and the O atom has a formal charge of −1. In the diagram on the right, the C atom has a formal charge of −1 and the O atom has a formal charge of zero. The diagram on the left is the better representation because it puts the negative formal charge on oxygen, which is more electronegative than carbon.
Part (b): Many students used $\Delta H°_{rxn} = \Delta H_{products} - \Delta H_{reactants}$ with the bond enthalpies and got a positive $\Delta H°_{rxn}$. Students did not always use all of the bond enthalpies in their calculations and got a number other than 246. Students multiplied the number of bonds by the bond energies.	$\Delta H° = \Sigma$(enthalpies of bonds broken) $-\Sigma$(enthalpies of bonds formed) $= 1505 \text{ kJ/mol} - 1751 \text{ kJ/mol}$ $= -246 \text{ kJ/mol}_{rxn}$
Part (c): Students indicated only that the structures were similar, therefore the $\Delta S°$ is close to zero. Students used $\Delta G = \Delta H - T\Delta S$ to explain that $\Delta S°$ must be close to zero for $\Delta G° < 0$.	The change from fulminic acid to isocyanic acid is a rearrangement of atoms with no change in phase or number of molecules.

Part (d):	
Students did not make a choice of HCNO or HNCO or did not make one consistent with their answer in part (b). Students indicated that the reaction was favorable because it was exothermic, without consideration of $\Delta S°$. Students indicated that products would be favored, but did not mention the equilibrium constant. Students invoked LeChatelier's principle or used Q≠K as justification. Students indicated that K was large (or small), but did not compare it to 1. Students indicated that K was negative or equal to zero.	Isocyanic acid (HNCO) will be present in higher concentration. $\Delta G°$ is essentially equal to $\Delta H°$ because $\Delta S°$ is essentially zero, so $\Delta G° \approx -246$ kJ/mol$_{rxn}$, indicating that the forward reaction is thermodynamically favorable. Since $\Delta G°$ is negative, $K > 1$ ($\Delta G° = -RT \ln K$), resulting in a higher concentration of products than reactants at equilibrium.
Part (ei):	
Students indicated that because the $[CO(NH_2)_2]$ decreased with time, that it was a first-order reaction. Students indicated that there was an exponent of 1 in the given rate law, so it must be first-order. Students indicated that because it had a half-life, it must be first-order. Students indicated that for a first-order reaction, a plot of $\ln[CO(NH_2)_2]$ vs time would be linear, but did show how the data given supported this. Students indicated that because $CO(NH_2)_2$ was the only reactant, the reaction must be first-order.	From inspecting the data table or the graph, it is evident that the decomposition reaction has a constant half-life, which indicates that the reaction is a first-order reaction.
Part (eii):	
Students used the incorrect units and/or calculated a negative k. Students calculated $\frac{\Delta \text{ concentration}}{\Delta \text{ time}}$ for an interval, and then used the rate law to solve for k.	Using either the half-life equation or the integrated rate law for a first-order reaction, $k = 0.069$ h^{-1}

Part (f):	
Students described an experiment that would change only temperature.	Perform the experiment at a different concentration of OH $^-$(aq) and measure how the concentration of $CO(NH_2)_2$ changes over time. (Other variables such as temperature should be held constant.)
Students described performing a titration with acid or base and then measuring pH.	
Students changed more than one variable in the experiment.	
Students indicated that they would plot [OH $^-$] versus time	
Students described adding an indicator or pH probe to monitor pH	
Students used a different weak acid.	
Student's indicated that they would run the reaction again in 0.1M NaOH.	
Students indicated that they would change [OH $^-$], but keep pH the same.	

Based on your experience at the AP® Reading with student responses, what advice would you offer to teachers to help them improve the student performance on the exam?

1. Have students practice calculating formal charges for Lewis structures.
2. Have students practice estimating ΔH°_{rxn} from bond enthalpies.
3. Remind students that thermodynamic favorability depends on both enthalpy and entropy.
4. Give students practice analyzing kinetic data. Make sure they refer to the data in their analyses.
5. Remind students to keep track of units in calculations.
6. Have students in their lab reports propose/design a related experiment to gain new information.

What resources would you recommend to teachers to better prepare their students for the content and skill(s) required on this question?

There are four years' worth of AP Chemistry free response questions and the associated scoring guidelines on the AP Chemistry exam page: https://apcentral.collegeboard.org/courses/ap-chemistry/exam?course=ap-chemistry
- Teachers could review elements of Q7 from the 2014 exam, Q5 from the 2015 exam, and Q2 from the 2016 exam with their students.

Topics: Gas Phase Equilibrium, Acid-Base Reactions, and Buffer Equilibria

Max. Points: 10   **Mean Score:** 2.95 ± 2.12

What were students expected to demonstrate in their response to this question?

This question assessed students' understanding of gas phase equilibrium, the ability to calculate an equilibrium constant using equilibrium partial pressures, to identify the two major components of an acidic buffer equilibrium system and to determine the buffer capacity of a solution. The last part of the question assessed students' ability to interpret a particulate diagram representing the major species in a buffer solution and to determine the pH relative to a solution where the pH = pK_a.

In this question the Learning Objectives (LO) assessed were 6.5, 6.18, and 6.20. The Science Practices (SP) assessed were 2.2, 2.3, 4.2, and 6.4.

In part (a) students were required to write a K_p expression for a given reaction. In part (b) students had to use reaction stoichiometry and an ICE table (or its equivalent) to determine the equilibrium partial pressures of reactants and products, and then to correctly calculate the value of K_p for the system by substitution. In part (c) students were expected to analyze the preparation of a buffer solution. Part (c)(i) required students to explain, using a net ionic equation, why mixing a strong base with a weak acid could result in a buffer solution. Part (c)(ii) required students to determine the relative proportions of strong base and weak acid needed to prepare a buffer with a pH = pK_a of the weak acid. In part (d) students were required to evaluate with justification the relative buffer capacities of two similar buffers (HNO_2/NO_2^- at pH = pK_a) at different concentrations prepared by different means. In part (e) students were required to interpret a particle-level representation of a buffer solution and to state with justification whether the represented buffer had a pH greater than, less than, or equal to pK_a.

How well did the students address the course content related to this question? How well did the students integrate the skills required on this question?

The mean score for Question 3 was 2.95 ± 2.12 out of possible 10 points. The distribution of scores on Question 3 is shown below:
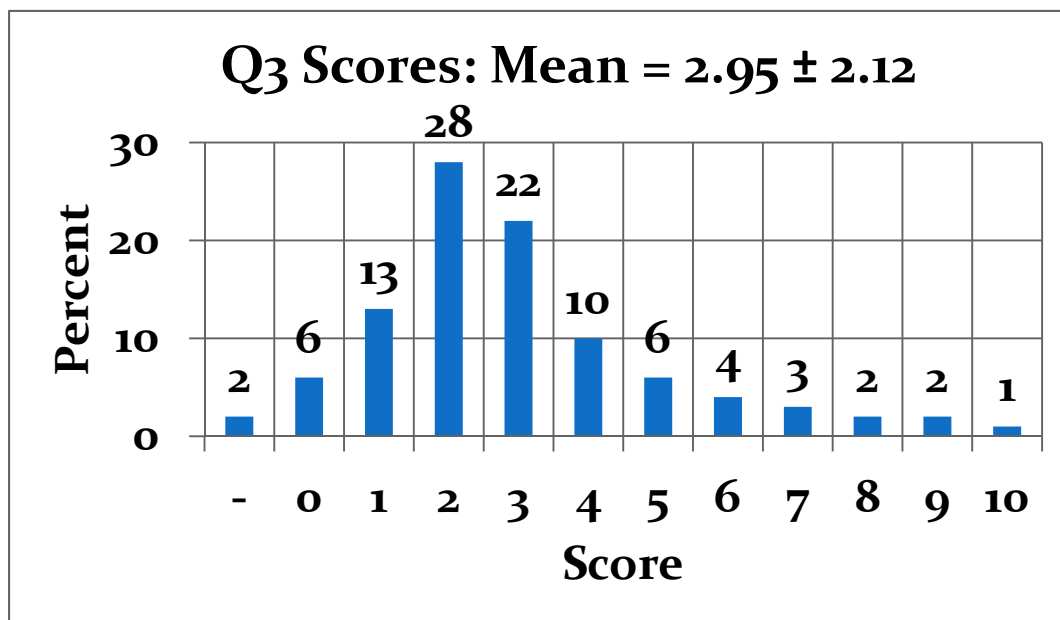
In part (a), given the equilibrium equation, $N_2(g) + O_2(g) \rightleftharpoons 2NO(g)$, most students wrote an equilibrium constant expression for K_p using square brackets, e.g., [NO] (indicating concentrations) instead the symbol "P_{NO}" (indicating partial pressures).

In part (b), many students failed to use an ICE table (or its equivalent) to determine the equilibrium partial pressures of the reactants. Students instead used the initial pressures of the reactants and calculated an incorrect value of K_p.

In terms of skills needed to be successful on parts (a) and (b), students did not generally demonstrate that they can apply mathematical routines to quantities that describe gas phase equilibrium. Students demonstrated they could algorithmically plug numbers into an equation, but they had no real conceptual understanding of reaction stoichiometry as applied to gas phase equilibrium. In terms of the use of representations and models to solve problems quantitatively, the majority of students did not understand the difference between the use of brackets, "[A]," indicating concentration and the use of the symbol "P_A," indicating partial pressure. Most answers did not demonstrate that students knew the difference between K_c and K_p. Most students did not know enough about equilibrium systems to calculate the equilibrium partial pressures. Understanding the stoichiometric relationships among species and the connection to a balanced chemical equation is an essential concept.

In parts (c), (d), and (e), students were asked to analyze various buffer systems. Most students demonstrated a rudimentary understanding of Brønsted-Lowry and Arrhenius acid-base theory with respect to writing an equation to represent an acid-base reaction. Most students demonstrated that they knew a base could neutralize an acid. About a third of the students could write a net ionic equation. However, the majority of students demonstrated a lack of understanding that a weak acid is mostly un-ionized in aqueous solution. The proper (conventional) representation of nitrous acid in solution is "$HNO_2(aq)$", the molecular form. Most students represented nitrous acid in solution as H^+ and NO_2^- resulting in an incorrect net ionic equation of $H^+ + OH^- \rightleftharpoons H_2O$. This is a key model in acid-base equilibrium theory. The majority of responses demonstrated that students had no real understanding of the basic representations used in acid-base theory. Many students did not know that all compounds containing sodium cations dissolve and ionize in water. Most students demonstrated a lack of integrating an application of the solubility rules to this problem.

The majority of students did not demonstrate an understanding of buffer systems. Most students did not identify or recognize that an acidic buffer system has two components, a weak acid and its conjugate-base. A portion of students had memorized the fact an acidic buffer solution was composed of a weak acid and its conjugate-base, but could not identify which acid or conjugate base made up the buffer. Most commonly, the hydroxide ion, OH^-, was identified as the base.

The majority of students demonstrated they had no understanding of buffer capacity, and they confused the terms "volume," "amount," "concentration," and "moles" in parts (c), (d), and (e). In part (ci), the net ionic reaction is a reversible, equilibrium reaction with a large K value (meaning the reaction "favors" formation of products), the best representation of this system is to use double equilibrium arrows

$$HNO_2(aq) + OH^-(aq) \rightleftharpoons NO_2^-(aq) + H_2O(l)$$
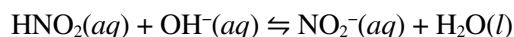
However, most general chemistry textbooks use a single arrow to represent the equation for a chemical reaction system that has a large value of K_{eq}. AP Chemistry teachers should discuss this issue with their students and encourage them to use the double equilibrium arrow to represent all equilibrium systems, including those systems with a large value for K_{eq}.

The majority of students did not compare the concentrations of the two buffer systems in part (d). Many students thought there were two different buffer systems: $NaOH/HNO_2$ and $NaNO_2/HNO_2$. Some students algorithmically used the Henderson-Hasselbalch equation to quantitatively calculate the pH in parts (cii) and (e). Students who used this algorithmic approach were generally more successful in answering parts (cii) and (e) compared to the students used a conceptual approach. The skill distinctly lacking in the vast majority of students on parts (d) and (e) was in reading the question and understanding the question was asking for a comparison of two buffer systems. Most students did not compare and contrast.

With respect to applying science skills and practices, the majority of students demonstrated clearly they could NOT use scientific representations and models to analyze buffer system problems qualitatively and quantitatively. Student had difficulty estimating numerical quantities describing equilibrium systems. Parts (c), (d), and (e) required students to design a plan for analyzing data to answer scientific questions and to identify patterns or relationships about acid-base reactions and buffer systems. The majority of students demonstrated that they did not have this skill, and they could NOT make claims and predictions about natural phenomena based on scientific theories and models involving acid-base equilibria. Finally, most students demonstrated they did not know how to analyze particulate diagrams representing buffer solutions. Because

students did not have good conceptual understanding of (1) equilibrium principles, (2) acid-base theory and (3) buffer systems, their performance on parts (c), (d), and (e) was poor.

What common student misconceptions or gaps in knowledge were seen in the responses to this question?

Common Misconceptions/Knowledge Gaps	Responses that Demonstrate Understanding
Parts (a) and (b): Writing a K_c equilibrium expression using brackets, "[N_2]" indicating concentration in units of molarity, instead of a K_p equilibrium expression using the symbol "P_{N2}" for partial pressure indicating the amount of the gas in units of atmospheres. Using the initial pressures of the reactants instead of setting up an ICE Table and determining the equilibrium pressures of the reactants. Not realizing that the partial pressure of NO(g) at equilibrium was given as 0.122 atm and that 2x = 0.122 atm. Omitting the 1:2 stoichiometric ratio between a reactant and product in the K_p equilibrium expression. Not squaring the equilibrium partial pressure of NO(g) in the equilibrium expression. Having units associated with the K_p equilibrium expression.	$$N_2(g) + O_2(g) \rightleftharpoons 2NO(g)$$ Initial 6.01 1.61 0 Change −x −x +2x Equilibrium 6.01−x 1.61−x 0.122 atm • 2x = 0.122 atm x = 0.0610 atm; Equilibrium Pressures: P_{N2} = 5.95 atm P_{O2} =1.55 atm P_{NO} = 0.122 atm • $K_p = (P_{NO})^2/\{(P_{N2})(P_{O2})\}$ • $K_p = (0.122)^2/\{(5.95\ \text{atm})(1.55\ \text{atm})\} = 0.00161$
Part (ci): Some students misunderstood that the partial neutralization of HNO_2 with OH^- is an equilibrium reaction with a large equilibrium constant, $K_{eq} = K_a/K_w$, that results in the formation of a buffer. Students wrote the strong acid vs. strong base net ionic equation: $H^+ + OH^- \rightarrow H_2O$ indicating a lack of understanding of the difference between and strong acid and a weak acid. Students were unable to identify the two components of an acidic buffer solution: a weak acid and its conjugate base. Some students wrote	In order to prepare an acidic buffer solution starting with nitrous acid, HNO_2(aq) and some NaOH(aq) can be added to react with some, but not all, of the HNO_2, producing aqueous nitrite ions and water as represented by the following net ionic equation: $HNO_2(aq) + OH^-(aq) \Longleftrightarrow NO_2^-(aq) + H_2O(l)$ The resultant solution contains a mixture of a weak acid and its conjugate base, which is a buffer solution.

that an acid and its common ion constituted a buffer solution. Many responses indicated that water is a buffer solution. In fact, water is not a buffer solution.	
Part (cii): Inappropriately, students used the formula $M_1V_1 = M_2V_2$ to calculate the volume of aqueous sodium hydroxide required to react with some of the HNO_2. The use of this formula resulted in an incorrect volume of NaOH. More importantly, students using this formula demonstrated that they held a misconception about the nature of buffer systems.	When half of the HNO_2 is converted to the conjugate base, the concentrations of HNO_2 and NO_2^- are equal; therefore the buffer has a pH equal to the pK_a.
Part (d): Students exhibited a complete lack of a conceptual understanding for what "buffer capacity" means for a buffer solution. Students often cited "more volume of HNO_2" as a reason for choosing a solution having the greater buffer capacity. The majority of students did not apply LeChatelier's principle and the common ion effect to their reasoning about buffers. Students exhibited a misconception when they failed to recognize that the two buffer solutions had the same pH, 3.40, each solution was buffering at pH = 3.40, but one buffer solution had a greater number of moles of HNO_2 and NO_2^- compared to the other buffer.	The buffer made by the second student is more resistant to changes in pH because it contains a higher concentration of HNO_2 and NO_2^- to react with added H^+ or OH^- ions
Part (e): Students did not know that the number of particles of HNO_2 and NO_2^- in the particulate diagram was a representation of the concentration of HNO_2 and NO_2^- in the buffer solution and this is related to the pH of the solutions.	When $[HNO_2] = [NO_2^-]$, the pH = pK_a = 3.40. As represented by the particulate diagram, $[HNO_2] > [NO_2^-]$. Using the Henderson-Hasselbalch equation to calculate the pH for this buffer solution, pH = pK_a + log$\{[NO_2^-]/[HNO_2]\}$, the log$\{[NO_2^-]/[HNO_2]\} < 0$, therefore the pH of this buffer solution will be less than 3.40.

Based on your experience at the AP® Reading with student responses, what advice would you offer to teachers to help them improve the student performance on the exam?

Early in the course, have students understand how to work all of the necessary functions on their calculator, especially the order of mathematical operations on their calculator. Have students use the same calculator they used for their AP Chemistry course on the AP Chemistry exam.

It is critical that students understand balancing chemical equations includes balancing both atoms and charge. Have students practice balancing both molecular equations and net ionic equations whenever feasible throughout the course.

When introducing equilibrium, first attempt to have students acquire a conceptual understanding of gas phase equilibrium by showing computer animations or computer simulations that are representations of chemical systems in equilibrium. Along with the simulations in the classroom, have students work problems involving particulate diagrams. Have students draw their own particulate drawings to demonstrate understanding of equilibrium. In the laboratory, have students do a laboratory activity using guided-inquiry at the exploration phase. When writing equilibrium equations, be sure students understand what the equilibrium arrows represent and when it is appropriate to use equilibrium arrows.

When introducing equilibrium calculations, be sure to link the balanced chemical equation to the format of ICE tables. Emphasize proper use of symbols such as brackets and the understanding of their use. Students should work problems involving K_c and K_p. Do experiments in which students work with different types of equilibrium systems including K_p.

When introducing acid-base equilibria, begin by showing computer animations and or simulations representing strong acid and weak acid aqueous systems. Have students focus their attention on the extent of ionization. Have students draw particulate diagrams of strong acid solutions and weak acid solutions. Have students work problems involving particulate diagrams involving determining the concentration of weak acids and strong acids and the pH of these solutions. Do a demonstration illustrating the difference in pH of strong acids and weak acids having the same concentration.

Have students practice writing balanced molecular equations and net ionic equations early and often throughout the term. When introducing the terms conjugate acid and conjugate base, avoid using the terms "strong conjugate acid" and "strong conjugate base".

Make sure students understand logarithms, what a pH actually is, and how to change from a pH to a concentration correctly.

When introducing hydrolysis of salts, do a demonstration involving the pH of various salts. Begin by showing computer animations and or simulations representing acidic, basic, and neutral salts. Have students focus their attention on the extent of ionization and on writing chemical equations that show the important species in solution. Have students draw particulate diagrams of salt solutions. Have students work problems involving particulate diagrams involving determining the pH of acidic salts, basic salts, and neutral salts. Have students do an experiment involving the hydrolysis of salts.

When introducing buffers, start the lesson with a demonstration involving three beakers containing different solutions all starting at pH = 7, and all with several drops of universal indicator. Have a set of test tubes showing a series of solutions of at different pH with universal indicator. Two of the solutions are acetic acid/sodium acetate buffer solution. In the third beaker is water. Place one drop of 1 M HCl in the buffer solution and one drop of 1M HCl in the H_2O. Do experiments with buffers so students understand what can and what cannot comprise a buffer. Have students make a buffer of a designated pH and explain with particulate diagrams. With a variety of different buffer systems, have students determine the buffer capacity. Reinforce the concept of weak and strong acids and weak and strong bases, and the "relative" strength of conjugate pairs by identify the two main components in various buffer systems. Do not use the term "common ion effect" to describe buffer composition or behavior.

Students should do a lab involving potentiometric titration of solutions (using pH meters). Students should make graphs of strong acid vs. strong base, weak acid vs. strong base. Have them identify on the graph the half-equivalence point and the equivalence point. Have students use particulate drawing to demonstrate understanding and include identifying points on a graph, especially, the buffer region. Have students do many types of titrations and make sure they are able to explain as well as calculate concentrations of different species at different points in the titration, especially at initial conditions; pK_a, at equivalence, and well beyond equivalence. Have students use particulate drawing and graphs to demonstrate understanding. Use computer animations and simulations of acid-base titrations to help reinforce students' conceptual understanding of acid-base titrations.

What resources would you recommend to teachers to better prepare their students for the content and skill(s) required on this question?

The AP Chemistry Guided Inquiry Experiments lab manual is a good resource to help strengthen student conceptual; understanding. There are two labs from this manual that could be used to help students address the misconceptions seen in this question:

- Lab 15: Buffering Activity
- Lab 16: Buffer Design

The teacher version of the lab manual can be found at the link below. You will need a password to access the lab manual: https://secure-media.collegeboard.org/digitalServices/pdf/ap/2014advances/ap-chemistry-lab-manual-2014.pdf

There are four years' worth of AP Chemistry free response questions and the associated scoring guidelines on the AP Chemistry exam page: https://apcentral.collegeboard.org/courses/ap-chemistry/exam?course=ap-chemistry

- Teachers could review elements of Q2 and Q4 from the 2014 exam, Q3 and Q6 from the 2015 exam, and Q2 and Q4 from the 2016 exam with their students.

Task: Interpret the results of a chromatogram

Topic: Chromatography, intermolecular forces

Max. Points: 4

Mean Score: 1.78 ± 1.21

What were students expected to demonstrate in their response to this question?

This question assessed students' ability to demonstrate the ability to interpret the results of a chromatography experiment correctly and to identify the least polar dye from among three dyes (A, B, or C).

In this question the Learning Objective (LO) assessed was 2.10. The Science Practices (SP) assessed were 4.2, 5.1, and 6.4.

In part (a) the dye that traveled the farthest on the chromatogram was the least polar. The students then were expected to use dye/solvent interactions and/or dye/stationary phase interactions to justify the response interpretation. The least polar dye has greater attractions to the nonpolar solvent, and/or the least polar dye has the weakest attractions for the polar paper. In part (b) students were expected to correctly identify an unknown from among the three known dyes. Since the solvent fronts for the two chromatograms were not equal, the justification for the unknown identification needed to reference retention factor values (or a description of retention factors) for the two chromatograms (unknown and selected dye).

How well did the students address the course content related to this question? How well did the responses integrate the skills required on this question?

The mean score for Question 4 was 1.78 ± 1.21 out of possible 4 points. The distribution of scores on Question 4 is shown below:
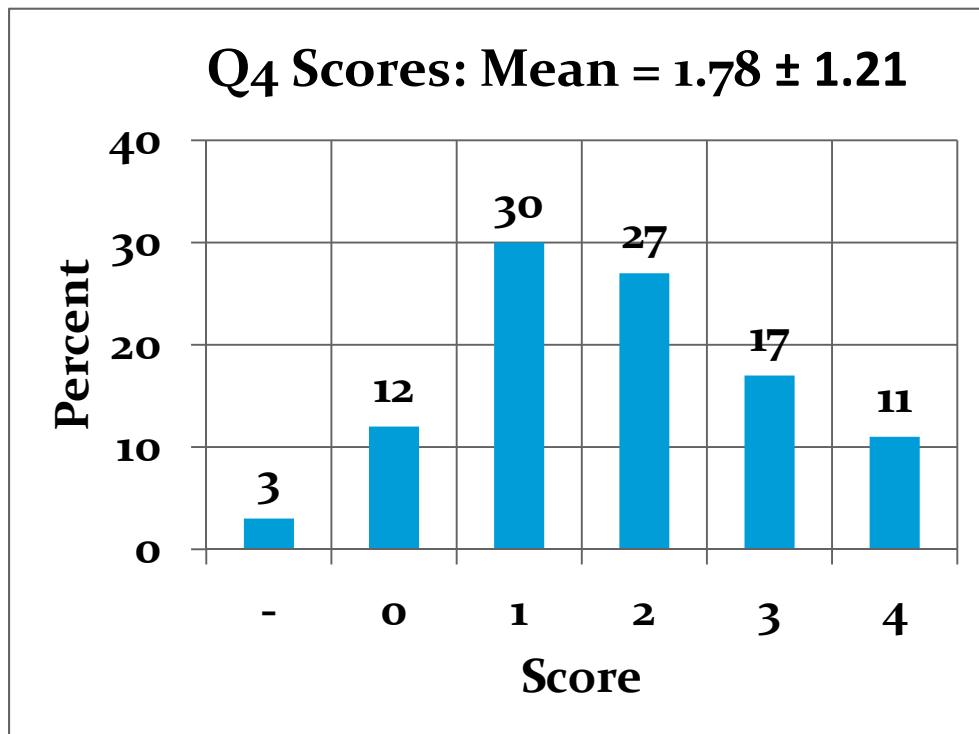
The part (a) response addressed the interactions of nonpolar dye (solute) with nonpolar solvent (mobile phase) and/or nonpolar dye (solute) with polar paper (stationary phase). Students had to understand that, in a chromatography experiment, a dye moves more if it is attracted to the mobile phase and it moves less if it is attracted to the stationary phase.

The part (b) response addressed interpretation of chromatograms to identify an unknown by comparison to three known dyes. Responses needed to reference the ratio of distance traveled by each dye compared to the origin to solvent front distance, the retention factor (R_f). Similar R_f values indicate the unknown has the same identity as one of the known dyes.

What common student misconceptions or gaps in knowledge were seen in the responses to this question?

In part (a)

- Students frequently did not know how to interpret the chromatogram to identify the least polar dye. Students commonly assumed that the dye that moved the least on the polar paper was the least polar dye.

- Students often did not know how to describe dye/solvent interactions or dye/paper interactions. Common statements included that the dye "repelled" the paper, or that the most polar dye "climbed" up the paper farther,

In part (b)

- Students did not know the definition or application of retention factor (R_f).

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
Responses stated that the least polar dye moved the least on the polar paper.	Dye C is the least polar dye since it moved farthest up the polar paper.
Responses compared similar heights of unknown and one of the three dyes instead of R_f values	The unknown is dye A since both dyes traveled about half the distance between the origin and the solvent front.
Responses often stated that molecules repelled each other.	The least polar dye had the weakest attractions for the polar paper.

Based on your experience at the AP® Reading with student responses, what advice would you offer to teachers to help them improve the student performance on the exam?

1. Be sure to discuss intermolecular interactions of the analyte molecules with the stationary phase and with the mobile phase when performing a chromatography experiment.
2. Be sure to have students calculate the retention factor values.

What resources would you recommend to teachers to better prepare their students for the content and skill(s) required on this question?

The AP Chemistry Guided Inquiry Experiments lab manual is a good resource to help strengthen student conceptual; understanding. There is one lab from this manual that could be used to help students address the misconceptions seen in this question:
- Lab 5: Chromatography

The teacher version of the lab manual can be found at the link below. You will need a password to access the lab manual:
https://secure-media.collegeboard.org/digitalServices/pdf/ap/2014advances/ap-chemistry-lab-manual-2014.pdf

Question #5   **Task:** Energy transfer involving combustion   **Topic:** Calorimetry, energy balance, error analysis

Max. Points: 4   **Mean Score:** 1.53 ± 1.27

### What were students expected to demonstrate in their response to this question?

This question required students to analyze the results of a heat transfer experiment in which a sample of water was heated by the combustion of 2-propanol.

In this question the Learning Objective (LO) assessed was 5.7. The Science Practices (SP) assessed were 4.2, 5.1, and 6.4.

Part (a) required students to use the appropriate experimental data to calculate the amount of energy transferred when a sample of water was heated by the combustion of 2-propanol. Part (b) required students to relate the amount of heat energy transferred from the combustion of 0.55 g of propanol to the amount of heat energy expected from the combustion of one mole of 2-propanol. Part (c) required students to make a choice and justify that choice. Justification problems are inherently difficult as they require students to express their ideas in clear statements. When the scientific language is not yet fully developed within the student, expressing justification regarding changes in an experiment makes this a difficult question.

How well did the students address the course content related to this question? How well did the responses integrate the skills required on this question?

The mean score for Question 5 was 1.53 ± 1.27 out of 4. The score distribution for question 5 is shown below:
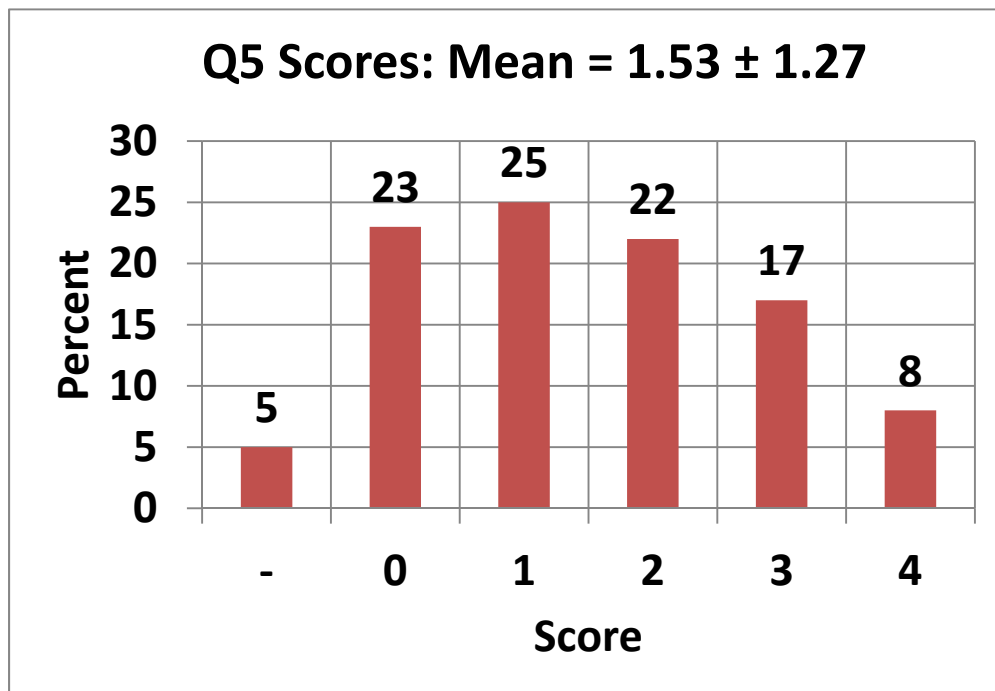
Many students were capable of correctly answering part (a) which required them to use specific heat capacity in the equation $q = mC\Delta T$ to calculate the thermal energy released when a specific amount of propanol was combusted. While students were likely to choose the correct equation for use in part (a), they need to work on their ability to interpret the meaning of the variables in that equation (and this applies globally to any use of an equation in a problem). This does not just mean understanding that m = mass, or that ΔT = change in temperature, but also how to connect the equation (and the variables within) to the experimental design. Some common variable interpretation errors included recognizing the appropriate mass for use in $q = mC\Delta T$. There were numerous values used for the mass, but the most common errors included the use of 125.55 g or 0.55 g. When students used 125.55 g, they were adding the 0.55 g mass of propanol combusted to the 125.00 g mass of the water in the beaker for use as the mass in the specific heat equation. Students using 125.55 g as the mass in $q = mC\Delta T$

are not connecting the actual experiment to the data. Clearly they do not understand that the 0.55 g of propanol is the source of thermal energy, while the 125 g of water in the beaker absorbs the thermal energy. If students made that link, they would understand that the 0.55 g and the 125 g cannot be added for use in the equation; they are not part of the same system.

Another common choice for mass was 0.55 g. In this case students, did not realize that if they used 0.55 g and 29.1 ℃ in the $q = mC\Delta T$, they were not correctly interpreting the experimental design because the 0.55 g of propanol is combusted, causing the temperature change in the water. Whether choosing 125.55 g or 0.55 g, it would seem that students are not interpreting the meaning of the variables with respect to the experimental design. This interpretation skill must also be extended to interpretation of data in a data table (SP 4 & 7). What does each type of data mean and what does it represent in the various parts of a system?

Temperature was another variable misinterpreted by students. By using 125.55 g, they must assume that the mixture of propanol and water had a temperature change of 29.1 ℃. Yet, the propanol temperature change was not measured because it is combusted. The water in the beaker is the only substance that experienced the temperature change from 22.0 to 51.1 ℃ (ignoring the beaker, ringstand, etc.). The skill of data interpretation as applied to experimental design is essential because it leads to correct use of data, in this case mathematical correctness. Another type of error was changing the ΔT from ℃ into the Kelvin scale. In fact, the ΔT in the reaction can be used as either Celsius or Kelvin (ΔT in Celsius = ΔT in Kelvin), but if you change the ΔT into Kelvin, you have incorrectly changed this data. While there are many times we require Kelvin for calculations, this is not one of them. Students were provided the specific heat capacity in the data table and they should be able to use that data to determine proper units. If the constant has specific units, in this case 4.18 J/g ℃, students should be able to determine without memorization the units needed for the other components of a problem.

In part b), many students attempted to use the $q = mC\Delta T$ to solve this problem. The question requires solving for heat energy and students seemed to be drawn to this equation because they know that $q = mC\Delta T$ produces a thermal energy answer. The answer to this question was, however, best found through mathematical manipulation of the answer in part a). In that answer, we find the kJ of energy produced when 0.55 g of propanol are combusted. Since the question requested the thermal energy evolved by one mole of propanol, it was necessary to create a conversion factor. Again, misinterpretation of the meaning of the data led many students to use $q = mC\Delta T$ incorrectly. This also may indicate that students do not understand the difference between various topics of thermal energy - in this case the difference between specific heat capacity and the heat of combustion. The use of $q=mC\Delta T$ for this problem shows a misconception that the propanol is changing temperature. Mathematically, many students demonstrated misunderstanding of rounding and truncating skills. Many responses showed that students were rounding numbers prior to use in calculations. These rounding methods caused significant error in the final answer. It is important that students understand that rounding should take place only at the conclusion of a calculation. Finally, a number of students incorrectly used stoichiometry and the coefficients from the given chemical equation in the problem. Students need to understand the appropriate times for these proportions.

In part c), confusion was created through student misinterpretation of the experimental design and how heat of combustion is the source of energy and is not being impacted by specific heat capacity. The students that stated the final temperature of the second experiment was greater than the first experiment usually explained this using comments about changes in specific heat capacity. Another misconception is that water combusted during the experiment. The combustion of propanol accounts for the energy produced, not the combustion of water. Water will be vaporized and as a result will consume some of the energy produced by the combustion of propanol as vaporization is an endothermic process. Some responses also made reference to the contamination of water as causing a decrease in the amount of energy that would be produced by the combustion of the same amount of propanol. Finally, responses confused the two systems; the water in the beaker and the alcohol/water mixture in the burner. Many believed that the contamination increased the amount of water in the beaker being heated and therefore required more thermal energy to heat.

What common student misconceptions or gaps in knowledge were seen in the responses to this question?

Common Misconceptions/Knowledge Gaps	Responses that Demonstrate Understanding
Systems in the experimental design are not separated Using 0.55 g in q = mCΔT. Using 125.55 g in q = mCΔT.	The use of 125.00 g in q = mCΔT Stating that the 0.55 g sample in the second experiment was a mixture of water and propanol and that only the propanol was combusted while water was evaporated Stating that there was less propanol combusted in the second experiment
The propanol and water both have a temperature change of 29.1 °C	The use of 125.00 g in q=mCΔT indicates student know the water in the beaker is the only substance with this temperature change
Use of q = mCΔT with ΔT = 29.1 °C to solve for the heat transferred by combustion of one mole of propanol	Use of heat of combustion data (kJ per 0.55 g) to solve for heat produced by one mole of propanol
Defining categories of heat; combustion, heat transfer using specific heat capacity, and vaporization	Use of heat of combustion data (kJ per 0.55 g) to solve for heat produced by one mole of propanol Stating that the water was part of the 0.55 g contaminated sample due to water vaporizing while the propanol was combusting
Some students believed combustion of water accounted for less heat energy	Indicating that less propanol is combusted with no reference to water Absorption of thermal energy by water in the contaminate samples leads to vaporization
Students believed the contamination lowered the amount of energy released by the combustion of water	Indicating that the loss of energy being produced was directly related to the amount of propanol burned rather than a change in chemical energy of the propanol

Based on your experience at the AP® Reading with student responses, what advice would you offer to teachers to help them improve the student performance on the exam?

Provide examples of experimental designs and have students explain interactions taking place. This will allow students to understand how specific data relates to certain components of the experiment and not to others (how the propanol is not connected to the change in temperature given).

Practice analysis of "errors" – This will enable all students to interpret data by understanding how changes in the data and the precision of the data will impact the overall measured outcome.

Practice interpreting data in two ways. First, students need to understand how data directly links to the experimental design. After gathering data, have students restate how that data was gathered so they recognize what part of the system was involved in that data. Second, students must apply appropriate mathematics to experimentally gathered data.

Practice rounding of numbers collected through measurement and also practice using proper rounding while using these numbers mathematically. Rounding numbers in an isolated setting is a good thing, but students need to know how to deal with rounding numbers while performing calculations.

Molar mass should not be the limiting factor in significant figures. Students should learn to use as many digits as possible in reporting molar masses.

Practice expressing ideas using proper vocabulary related to a chemistry concept. When students provide a written explanation their answers can be extremely vague and open to interpretation. Have students share answers so that they can experience each other's responses. This will lead to students gaining an understanding of the level of specificity they need to provide in a written explanation.

Have students perform calorimetry labs similar to the design in this problem.

Practice calculations to eliminate simple math mistakes, including calculator issues and transcribing data from the data table to the calculation.

What resources would you recommend to teachers to better prepare their students for the content and skill(s) required on this question?

The AP Chemistry Guided Inquiry Experiments lab manual is a good resource to help strengthen student conceptual; understanding. There is one lab from this manual that could be used to help students address the misconceptions seen in this question:

- Lab 12: Calorimetry

The teacher version of the lab manual can be found at the link below. You will need a password to access the lab manual: https://secure-media.collegeboard.org/digitalServices/pdf/ap/2014advances/ap-chemistry-lab-manual-2014.pdf

There are four years' worth of AP Chemistry free response questions and the associated scoring guidelines on the AP Chemistry exam page: https://apcentral.collegeboard.org/courses/ap-chemistry/exam?course=ap-chemistry

- Specifically, you could review with your students elements of Q7 from the 2015 exam and Q1 from the 2016 exam

Question #6

Task: Solubility of Mg(OH)₂ , Lattice Energy of Mg(OH)₂, Sr(OH)₂

Topic: Equilibrium, Coulomb's law

Max. Points: 4   **Mean Score:** 1.11 ± 1.19

What were students expected to demonstrate in their response to this question?

This question required students to determine the solubility of a sparingly soluble salt in aqueous solution and then to provide a rationalization for the differences in lattice energy between two crystalline ionic compounds.

In this question the Learning Objectives (LO) assessed were 2.24, 2.28, 2.30, 2.32, and 6.22. The Science Practices (SP) assessed were 1.1, 2.2, 2.3, 6.2, 6.4, and 7.1.

In part (a) students were asked to determine the solubility of a saturated $Mg(OH)_2$ solution, given the K_{sp} for the salt. In part (b) students were provided with a definition of lattice energy. They were given the lattice energies of $Mg(OH)_2$ and $Sr(OH)_2$, which are 2900 kJ/mol and 2300 kJ/mol, respectively. With this information, they were required to provide a rationale for the relative strengths of the lattice energies. A proper rationalization, at the AP Chemistry level, uses the relative sizes of magnesium and strontium cations to qualitatively gauge the interionic distance between the cation and hydroxide and its effect on the magnitude of the interionic Coulombic interaction.

How well did the students address the course content related to this question? How well did the responses integrate the skills required on this question?

The mean score for Question 6 was 1.11 ± 1.19 out of possible 4 points. The distribution of scores on Question 6 is shown below:

Q6 Scores: Mean = 1.11 ± 1.19

Score	Percent
-	7
0	35
1	26
2	17
3	11
4	5
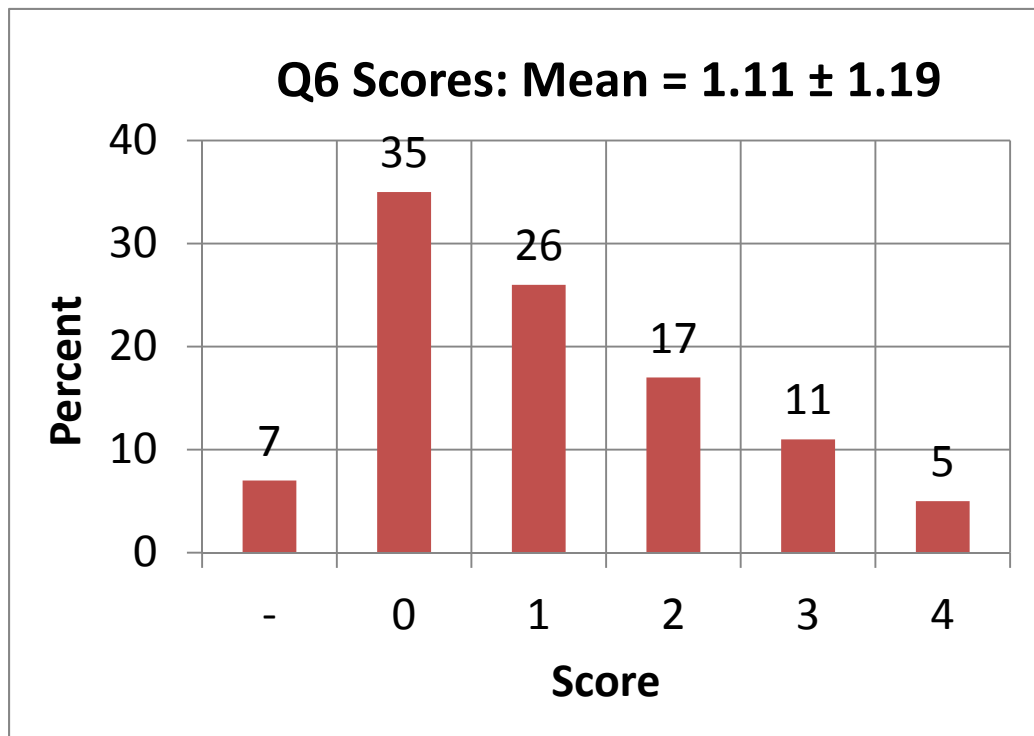
In part (a), student responses typically acknowledged the necessity for determining the solubility of $Mg(OH)_2$ in calculating the mass of the salt dissolved, and in this respect they addressed the intent of the question. However, integration of the chemical knowledge and mathematical skills necessary to solve the problem proved more difficult. While a minority of students formally illustrated the equilibrium shift for the salt in aqueous solution using an ICE table, more often many would attempt to recall an algorithm (i.e., $K_{sp} = 4x^3$) and apply this in determining the solubility, with varying degrees of success. There were a number of mathematical errors observed in the use of this algorithm (such as determining a square root rather than a cube root, forgetting to double the hydroxide concentration, etc.). In some instances, the K_{sp} was mistaken for the solubility of the salt, and on less frequent occasions, an unrelated value such as the molar volume of a gas at STP, was applied. These errors suggest a need to improve skills relating to the selection and application of mathematical models in particular contexts.

In part (b), a specific deficiency in the use of precise language made many student responses unclear and difficult to evaluate. This deficit suggests that students struggle to "construct explanations of phenomena based on evidence." For example, student responses often addressed the relative sizes of Sr^{2+} and Mg^{2+} cations, as intended by the question. However, students frequently referred to a comparison between Sr and Mg atoms, rather than the cations; occasionally, these species were even referred to as molecules. A significant number of responses also invoked other periodic trends, including ionization energy, electron affinity or electronegativity, or even unrelated properties such as molar mass, to explain the differences between the two ions. Similar difficulties were noted when students attempted to rationalize the relative lattice energies of $Sr(OH)_2$ and $Mg(OH)_2$. Students often acknowledged that the relative sizes of the cations would play some kind of role, but the responses were often nebulous. Responses frequently stated that an increased distance would result in decreased attractive forces, but did not specify that the distances (or forces) involved were between the cations and anions within the respective salts. Instead, students would refer to the distance between a nucleus and an electron, between (unspecified) nuclei, occasionally between electrons, or even between distinct $Sr(OH)_2$ units (or $Mg(OH)_2$ units) within the material, referring to the "radius of $Mg(OH)_2$" as a whole rather than the interionic distance. This latter explanation indicates a failure of students to distinguish between the ionic bond model and the covalent bond model.

What common student misconceptions or gaps in knowledge were seen in the responses to this question?

Common Misconceptions/Knowledge Gaps	Responses that Demonstrate Understanding
• In part (a), common misconceptions included: Identifying K_{sp} as the molar solubility. Omitting the 2:1 stoichiometric ration between cation and anion, or omitting $2^2 = 4$ in the calculation of the solubility. Miscalculating the cube root of x^3 when determining the solubility. Omitting the volume of solution, or using the volume incorrectly, when determining the moles of $Mg(OH)_2$ dissolved. Using an unrelated value in the calculation, such as the molar volume of a gas at STP (22.4 L/mol).	• A proper response addressing these misconceptions would be: $$Mg(OH)_2 \leftrightarrow Mg^{2+} + 2\,OH^-$$ I: --- , 0 , 0 C: $-x$, $+x$, $+2x$ E: --- , x , $2x$ $K_{sp} = [Mg^{2+}][OH^-]^2 = (x)(2x)^2 \Rightarrow$ $1.8 \times 10^{-11} = 4x^3 \Rightarrow x = 1.65 \times 10^{-4}\,M = [Mg(OH)_2]$ 1.65×10^{-4} mol/L $\times 0.100$ L $\times 58.32$ g/mol $= 9.6 \times 10^{-4}$ g $Mg(OH)_2$

• In part (b), common misconceptions regarding cation size included: Referring to ions as atoms, molecules, or other terms without distinction. Comparing other properties of Mg^{2+} and Sr^{2+} rather than the ion sizes (e.g., ionization energy, electronegativity of the respective atoms, electron affinity), or attributing the size difference to something other than an increase in occupied energy levels (e.g., increased subshells, molar mass, etc.)	• A proper response addressing these misconceptions would be: "The Sr^{2+} ion is larger than the Mg^{2+} ion because it has additional occupied energy levels (or shells)…"
• Common misconceptions regarding interionic distance and interionic attractions included: Referring to a general "increased interaction" without specific reference to the relevant ions. Referring to Coulomb's law with respect to an interaction that is not between relevant ions (e.g., nucleus/electron, cation-cation, electron-electron, etc.). Referring to a distance between the nucleus and valence electrons, rather than between ions in the crystal lattice.	• A proper response addressing these misconceptions would be: "…Coulomb's law states that the force of attraction between cation and anion is inversely proportional to the square of the distance between them. Since the distance between Mg^{2+} and OH^- is shorter than the distance between Sr^{2+} and OH^-, the attractive forces in $Mg(OH)_2$ are stronger and therefore its lattice energy is greater."

Based on your experience at the AP® Reading with student responses, what advice would you offer to teachers to help them improve the student performance on the exam?

In general:
- Scientific terms have precise meanings, and therefore the proper term must be used in the proper context. Students should practice using the proper terminology when discussing chemical phenomena.
- Students should take the time to write clearly and in complete sentences. Often, understanding is lost, and potential points remain unearned, when students do not plainly indicate their meanings. Comparisons should be clear; for example, when comparing between ions, "Mg^{2+} has a smaller radius than Sr^{2+}" is clearer than "Mg^{2+} is smaller."

In part (a):
- It is worth the effort to describe a chemical equilibrium system using the equilibrium expression and an ICE table. Shortcuts or memorized algorithms often lead to conceptual or mathematical errors. Students should understand the difference between a square root and a cube root, and to properly calculate one or the other.
- Students should verify that units are consistent throughout the calculation steps. Often, the error of omitting volume of solution in determining the mass of $Mg(OH)_2$ dissolved could have been avoided if units were more carefully observed.

In part (b):
- The electronegativity of an element is a property that is only relevant in the context of a covalently bonded molecule. Electronegativity values or differences do not address the relative strength of a bond, only its relative polarity. Electronegativity is irrelevant when addressing Coulombic interactions within the ionic bond model. Likewise, periodic properties other than size are not germane to this question. Students should practice applying periodic properties in an appropriate context.
- When discussing Coulombic interactions, students must specifically indicate which species are involved. In this question, two types of Coulombic interactions—those between the nucleus and an electron within an ion, and those between cations and anions within the lattice—are present. The former affects the size of the ion, and the latter affects the interionic distance, which in turn impacts the lattice energy. It is unfortunate that the distance between

either pair of particles is typically assigned the variable r, but it is nonetheless important to distinguish the two. Perhaps the distance between ions could be labeled as d to reduce the confusion. Sketching particle-level diagrams of lattices that illustrate the interplay between ions may also be useful.

What resources would you recommend to teachers to better prepare their students for the content and skill(s) required on this question?

There are four years' worth of AP Chemistry free response questions and the associated scoring guidelines on the AP Chemistry exam page: https://apcentral.collegeboard.org/courses/ap-chemistry/exam?course=ap-chemistry
- Teachers should review elements of Q1 from the 2014 exam, Q4 from the 2015 exam, and Q1 from the 2016 exam with their students.

Task: Electrochemistry—choose the titrant

Topic: Electrochemistry, $E°$ values, thermodynamic favorability, $\Delta G°$

Max. Points: 4   **Mean Score:** 1.41 ± 1.31

## What were students expected to demonstrate in their response to this question?

This question required students to use their knowledge and understanding of electrochemistry to answer a two-part question about choosing an appropriate titrant for use on a redox titration.

In this question the Learning Objectives (LO) assessed were 3.9 and 3.12. The Science Practices (SP) assessed were 2.2, 2.3, 4.2, 5.1, and 6.4.

In part (a) the students had to use standard reduction potentials of half-reactions to calculate the standard cell potential for two titration reactions. In determining the concentration of hydrogen peroxide, H_2O_2, in a solution of hydrogen peroxide, there were two possible titrants, either dichromate ion, $Cr_2O_7^{2-}(aq)$ or cobalt(II) ion, $Co^{2+}(aq)$. In answering parts (a)(i) and (a)(ii), students needed to recognize when to reverse the sign of the standard reduction potential ($E°$) of a particular half-reaction. In addition, students needed to recognize that $E°$ is an intensive quantity, which means its value should not be multiplied by the stoichiometric factor used to balance the electrons. Students needed to recognize that both calculations in part (a) are linked to part (b). Parts (b)(i) and (b)(ii) dealt with the relationship between two driving forces of a chemical reaction: standard cell potential, $E°$, and standard Gibbs free energy, $\Delta G°$. $E°$ values are independent of the number of electrons transferred, while $\Delta G°$ ($\Delta G° = -nFE°$) is an extensive property that depends on the number of electrons transferred. The students were asked to choose the titrant for which the titration reaction is thermodynamically favorable at 298 K and then calculate the value of $\Delta G°$ for the reaction between the chosen titrant and $H_2O_2(aq)$.

How well did the students address the course content related to this question? How well did the responses integrate the skills required on this question?

The mean score for Question 7 was 1.41 ± 1.31 out of possible 4 points. The distribution of scores on Question 7 is shown below:

Q7 Scores: Mean = 1.41 ± 1.31

Score	Percent
-	8
0	24
1	26
2	18
3	14
4	9
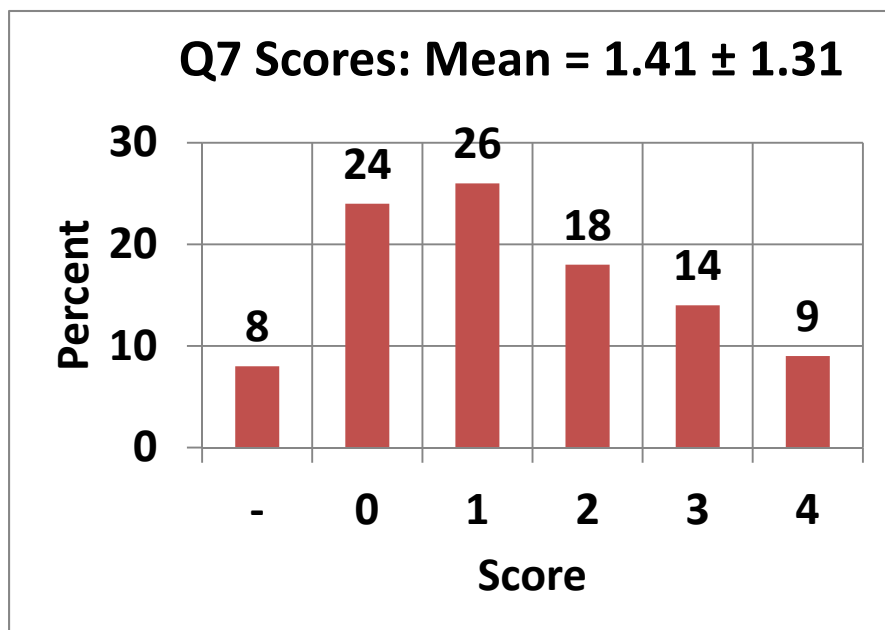
In part (a), the student responses generally acknowledged that a redox reaction involves oxidation and reduction. Many responses were able to balance the redox reactions with the appropriate number of electrons, albeit, there were many that did

not properly balance the redox reactions. Many students recognized that they had to reverse the sign of the standard reduction potential if the half-reaction is reversed to make it oxidation. Many students recognized that $E°$ is an intensive quantity, which means it does not depend on the coefficients in the half-reactions. However, some responses reversed the sign of the wrong half-reaction and others considered $E°$ as an extensive property by multiplying by the coefficients in the half-reactions. Students must recognize that the overall electrical potential of galvanic cells can be calculated by identifying the oxidation half-reaction and reduction half-reaction, and using a table of Standard Reduction Potentials. Students should be able to justify claims with evidence, such as justifying a reaction as being a redox reaction based on evidence regarding oxidation states.

In part (b), there was a specific deficiency in the use of the precise terminology, which made some responses difficult to evaluate. A common example is explaining the choice of the right titrant using standard reduction potential instead of standard cell potential. Students had the choice to explain thermodynamic favorability in the first part of the question using either the standard cell potential or the standard Gibbs free-energy. Many did very well in picking the right titrant and explaining that the standard cell potential is positive or the standard Gibbs free-energy is negative. Many others missed the point by using the wrong terminology for $E°$. Once the correct titrant was chosen, the calculation of $\Delta G°$ was generally successful with a few math errors. When the calculation of $\Delta G°$ was wrong, it was typically because the student did not choose the right number of electrons, forgot to monitor the sign, or did not do the J to kJ conversion correctly.

In terms of the course content related to this question, it is expected that "the student can make qualitative or quantitative prediction about galvanic or electrolytic reactions based on half-cell reactions and potentials and/or Faraday's laws." In addition, "the student is able to determine whether a chemical or physical process is thermodynamically favorable by calculating the change in standard Gibbs free-energy."

What common student misconceptions or gaps in knowledge were seen in the responses to this question?

Common Misconceptions/Knowledge Gaps	Responses that Demonstrate Understanding
• In part (a), common misconceptions included: Selecting the wrong half-reaction for H_2O_2 Forgetting that redox reaction means both oxidation and reductions occur. Using $E°$ as an extensive quantity. Reversing $E°$ for reduction and/or not reversing $E°$ for oxidation.	• A proper response addressing these misconceptions would be: $E° = 1.33 – 0.70 = 0.63$ V Here, the standard reduction potential for the half-reaction with dichromate (reduction) is 1.33 and this value is taken directly from the Table. The standard reduction potential for hydrogen peroxide (oxidation) has been reversed from the value given on the Table from 0.70 V to -0.70 V. Clearly, there is both oxidation and reduction (redox reaction).

• In part (b), common misconceptions regarding choosing the right titrant included: Identifying standard reduction potential as standard cell potential. Referring to the positive standard reduction potential instead of the positive standard cell potential. Stating that the $E°$ value of the correct titrant is "greater" instead of saying it is "positive."	• A proper response addressing these misconceptions would be: Choosing the right titrant and justifying the choice by either saying $E°$ is positive or $\Delta G°$ is negative for the reaction to be thermodynamically favorable.
• Common misconceptions regarding the calculation of $\Delta G°$ included: Not recognizing that n stands for the number of moles of transferred electrons and not moles of individual reactants or products. Not using the correct number of transferred electrons. Using the wrong conversion factor between J and kJ. Losing the sign of $\Delta G°$ in the reported value.	• A proper response addressing these misconceptions would be: Using the equation $\Delta G° = -nF\,E°$ with the correct number of moles of transferred electrons, consistently correct voltage and the right unit.

Based on your experience at the AP® Reading with student responses, what advice would you offer to teachers to help them improve the student performance on the exam?

In general:
- Scientific terms have specific meanings, and therefore the proper terminology must be used in the proper context. Students should practice using the proper terminology when analyzing redox reactions. There is a difference between standard reduction potential and standard cell potential.
- Students should be trained to be concise and more direct in their answers to questions.

In part (a):
- In a balanced chemical redox equation, have students practice identifying the species that are being oxidized and the species that are being reduced.
- Have students practice identifying the correct half-reactions that combine to give the overall cell reaction.
- Have students practice when it is necessary to reverse the sign of the standard reduction potential.
- Have students practice explaining why you do not need to multiply by the stoichiometric factor used to balance the electrons, because $E°$ is an intensive quantity.

In part (b):
- Have students practice predicting the thermodynamically favorable electrochemical cell reaction based on the sign of $E°$ (needs to be positive for a reaction to be thermodynamically favorable). For two calculated values where one is positive and the other negative, saying that $E°$ of one value is greater does not mean the same as saying one is positive for thermodynamic favorability.
- Have students practice explaining whether a redox reaction is thermodynamically favorable in terms of either the standard cell potential, $E°$, or the standard Gibbs free-energy, $\Delta G°$.

What resources would you recommend to teachers to better prepare their students for the content and skill(s) required on this question?

There are four years' worth of AP Chemistry free response questions and the associated scoring guidelines on the AP Chemistry exam page: https://apcentral.collegeboard.org/courses/ap-chemistry/exam?course=ap-chemistry
- Teachers could review elements of Q3 from the 2014 exam and Q1 from the 2015 exam with their students.