Chief Reader Report on Student Responses:

2022 AP® Chemistry Free-Response Questions

• Number of Students Scored	124,780		
• Number of Readers	412		
• Score Distribution	Exam Score	N	%At
	5	15,554	12.5
	4	21,174	17.0
	3	30,610	24.5
	2	29,392	23.6
	1	28,050	22.5
• Global Mean	2.73		

The following comments on the 2022 free-response questions for AP® Chemistry were written by the Chief Reader, Kyle Beran of Angelo State University. 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

Task: Salicylic acid
Topics: Error analysis, intermolecular forces, titrations
Max Score: 10
Mean Score: 4.44

What were the responses to this question expected to demonstrate?

Question 1 presented students with a variety of questions concerning salicylic acid ($HC_7H_5O_3$).

Part (a) of this question required students to apply the concepts of stoichiometry (Learning Objective SPQ-4.A, Science Practice 5.F from the *AP Chemistry Course and Exam Description*) to predict the mass of salicylic acid produced from a given mass of methyl salicylate along with the mole ratio between the two substances.

Part (b) asked to justify a claim regarding the percent yield of the reaction in part (a) (SPQ-4.A, 6.G). The response expected students to justify that the loss of mass of the acid during the filtration process could be due to the solubility of the acid.

The intent of part (c) was for students to recognize that the amount of heat required to melt a sample of solid salicylic acid involves the sum of two quantities to determine the total heat required to complete the change of state: heat required to increase the temperature of the solid to the melting point and the heat required to melt the solid into the liquid phase (ENE-2.D, 5.F). Part (c) was worth 2 points. The first point was earned for the correct calculation of either the amount of energy required to heat the acid up to its melting point or the amount of energy required to melt the acid at its melting temperature. The second point was earned for correctly determining the other energy quantity and the sum of the energies for the two heating processes.

Part (d) required students to analyze the molecular structures of methyl salicylate and salicylic acid to explain the difference in the melting point of each substance based on the magnitudes of the given types of intermolecular forces present in each molecule (SAP-5.B, 4.C).

The students were provided a titration curve for the titration of a salicylic acid solution with NaOH in part (e). The students were asked to estimate the pK_a of the acid (SAP-9.C, 2.D).

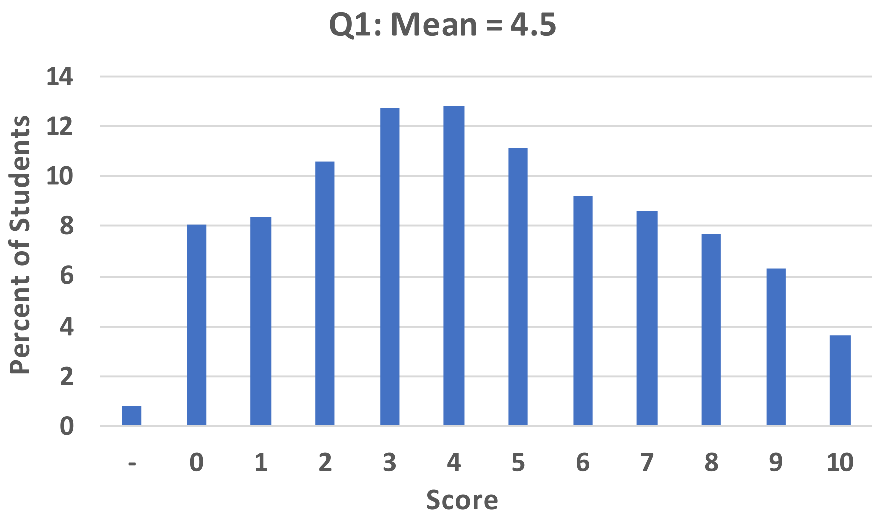
Part (f) asked students to determine the relative concentrations of the species in a conjugate acid–base pair for salicylic acid at a point during the titration where the pH value is higher (more) than the pK_a determined in part (e) (SAP-9.D, 4.A).

Part (g) required that the students calculate the pK_a of benzoic acid given the K_a value (SAP-9.C, 5.F).

The titration curve of salicylic acid from part (e) was presented to the students in part (h). Given an initial pH of the benzoic acid solution and using the calculated pK_a value from part (g), students were asked to draw a representative titration curve for benzoic acid. Part (h) consisted of 2 points. The first point was earned for starting the curve at the correct initial pH of the benzoic acid (pH = 3.11) and drawing the curve through the pK_a of 4.2 at the half-equivalence point of the titration (5 mL). The second point was earned for indicating that the equivalence point is reached after 10 mL of NaOH has been added and that the overall shape of the titration curve is consistent with a weak acid/strong base titration. Both points align to SPQ-4.B and 3.A.

How well did the responses 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 1 was 4.5 out of a possible 10 points, with a standard deviation of 2.8 points. The distribution of scores on this question is shown below.



Part (a) was an accessible point for the majority of students. Student responses successfully integrated the skills required, using dimensional analysis, to obtain the correct value reported to the correct number of significant figures.

Students performed moderately well on part (b), with a slight majority successfully understanding the conservation of mass during the dissolution process. The students also correctly applied the concept of solubility to the loss of mass of salicylic acid during the filtration.

A slight majority of students earned the first point in part (c). Students were able to correctly set up the equation and calculate the heat required to complete one of the two processes (changing the temperature of the solid or melting the solid into the liquid phase). Of the two, students more often correctly determined the amount of heat required to increase the temperature of the solid to the melting point. The majority of students did not earn the second point in part (c). Most frequently, these students did not recognize that there were two components to melting the crystals: heating to the melting point and then melting the solid into the liquid phase.

Part (d) was a challenging prompt for the students. The students correctly identified the structural differences between the two compounds and correlated these differences in the magnitude of the intermolecular forces, respectively.

Equally challenging for students was part (e). The successful students were able to identify the location of the half-equivalence (5 mL) and use the graph to estimate the pK_a of the acid.

Part (f) was challenging. By comparing the pH of the titration solution (pH = 4.00) to the pK_a value from part (e), successful students were able to determine that this point of the titration occurs after the half-equivalence point and correlate that at a pH of 4.00, this solution would have a higher concentration of the conjugate base (salicylate ion) than of the weak acid.

Part (g) was the most accessible point on Question 1. The majority of students were able to correctly calculate the pK_a of benzoic acid, given its K_a value.

Part (h) was challenging for the students. Students struggled to correctly draw the titration curve through the half-equivalence point (5 mL and pH = 4.20) as well as successfully indicating an inflection point in the curve at the equivalence point (10 mL of NaOH). Students also had a general misconception regarding the general shape of a weak acid/strong base titration curve.

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) • The most common error concerned significant figures. Based on the data provided, students were required to report the result of their calculation to three significant figures (0.272 g).	Part (a) • Starting the calculation with the provided mass of methyl salicylate (0.300 g), successful students were able to correctly convert to moles of methyl salicylate (dividing by the molar mass), then convert from moles of methyl salicylate to moles of salicylic acid (using the given 1:1 mole ratio), and finally convert from moles of salicylic acid to grams (multiplying by the molar mass of the acid).
Part (b) • Students did not realize that the loss of mass during filtration was due to the solid dissolving. • Students did not recognize that the solubility of the acid could account for the percent yield being less than 100%.	Part (b) • Common correct response: the loss of mass was due to the dissolving, or solubility, of the solid during filtration. • Several responses calculated that 13% of mass loss would require ≈16 mL of water during the filtration process.

Part (c) • Students did not calculate the quantity of heat required to complete both processes (increasing the temperature to the melting point and the melting of the solid) and/or did not calculate the total heat required. • Less common misconceptions were reporting the incorrect units and using the enthalpy of fusion rather than $q = mc\Delta T$ to calculate the heat required to increase the temperature up to the melting point.	Part (c) • First point: Students used the correct mathematical equation for determining either the amount of heat required to increase the temperature to the melting point, or the amount of heat required to melt the solid to the liquid phase. Students more commonly calculated for the heating step than the melting step. • Second point: Students correctly calculated both quantities of heat and surmised that the total amount of heat required to melt the salicylic acid sample was the sum of the two values.
Part (d) • Although students successfully recognized that salicylic acid possesses a greater number of hydrogen bonding sites than methyl salicylate, they did not relate this difference to the difference in the magnitudes of the intermolecular forces. • Less common knowledge gap demonstrated by students were those who focused on a different intermolecular force, and not hydrogen bonding.	Part (d) • Students recognized that salicylic acid possesses more hydrogen bonding sites than methyl salicylate; therefore, salicylic acid has stronger intermolecular forces. • Many responses then correlated the stronger intermolecular forces in salicylic acid to a greater energy requirement to overcome these forces and melt the solid.
Part (e) • The most common misconception was that students did not know how to identify the point on the graph corresponding to the pK_a of the weak acid.	Part (e) • Those students who understood how to interpret the titration curve correctly identified the pK_a as 3.0 or 3.1.

Part (f) • Students had a difficult time correlating relative concentrations of the weak acid and conjugate base to a specific point on the titration curve. • While students correctly identified that the conjugate base had the higher concentration, they were unable to explain why that was the case. • Students did not connect the half-equivalence point to [weak acid] = [conjugate base]. • Students had a difficult time communicating that after the half-equivalence point in the titration, the [conjugate base] > [weak acid].	Part (f) • Successful students were able to explain that since the pH of 4 occurred after the half-equivalence point of the titration (pH = 3), then the [conjugate base] > [weak acid].
Part (g) • The most common error was that students did not show their work or the mathematical process they employed to obtain the pK_a value.	Part (g) • Successful students showed their setup and correctly calculated the pK_a for benzoic acid: $-\log(6.3 \times 10^{-5}) = 4.20$.
Part (h) • The most common error for the first point in part (h) was not drawing the titration curve through the correct half-equivalence point. • The most common misconception for the second point was not recognizing that the equivalence point for both titrations occurs when 10 mL of NaOH had been added.	Part (h) • Successful students correctly used the initial pH of the solution and started their titration curve at this pH. Students then correctly drew their curve to pass through the half-equivalence point in order to earn the first point in part (h). • Students then correctly continued the curve toward the addition of 10 mL of NaOH and indicated an inflection point in their curve at the 10 mL mark and then ended the curve at or near the pH of the salicylic acid titration curve.

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

1. Discuss various ways in which a chemical reaction does not result in 100% yield. For lab experiments that involve a calculation of theoretical and percent yield, have students account for experimental reasons for a deviation from the theoretical yield in their lab reports.
2. When presented with the heating or cooling processes, have the students take the time to draw a heating/cooling curve.
   a. On the y-axis, have the students note the freezing point and boiling point and include provided temperature data (T_{mp}, T_{bp}, $T_{initial}$, T_{final}).
   b. Have students count the number of line segments from the $T_{initial}$ to T_{final} = number of different values of heat required to determine the total heat ($q_{\text{total}} = q_1 + q_2 + \ldots$).
   c. Describe the different mathematical routines that correspond to various parts of the curve.
3. Help students conceptually understand the quantitative process involved in the titration process.
   a. Have students draw particulate representations of a titration mixture at the half-equivalence point (equal numbers of moles of acid and conjugate base), as well as at various other points of the titration to ensure they have an accurate mental model of the ratio of acid and conjugate base throughout the titration.
   b. Have the students use Henderson Hasselbalch equation with the pK_a and pH at specific points in the titration to determine the relative concentrations of each species in a conjugate acid base pair, both before and after the half-equivalence point.

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

- Teachers can use AP Classroom to direct students to the AP Daily videos for Topics 3.1, 3.2, 4.5, 4.6, 6.4, 8.3, 8.4, 8.5, and 8.7.
- Teachers can use AP Classroom to direct students to the 2022 AP Exam On-Demand Review Session 1: Graphical Analysis Review and the 2021 Session 5: Experimental Methods & Analysis of Free-Response Questions.
- Teachers can give students practice with matching particulate diagrams to various points on a titration curve (see worksheet at https://goo.gl/tYDHeu) and follow up by having students draw their own particulate representations (see worksheet at https://goo.gl/QU29gs).
- Teachers can assign topic questions and/or progress checks in AP Classroom to monitor student progress and identify areas that may need additional instruction or content and skill development.

Question 2

Task: Methanol decomposition
Topics: Thermodynamic state functions, equilibrium, oxidation numbers
Max Score: 10
Mean Score: 5.29

What were the responses to this question expected to demonstrate?

Question 2 exposed students to a variety of prompts concerning the decomposition of methanol.

Part (a) of this question required the students to identify if an atom has been oxidized or reduced and to justify in terms of oxidation numbers (Learning Objective TRA-2.A, Science Practice 4.A from the *AP Chemistry Course and Exam Description*).

Part (b) asked students to complete the Lewis structure for a diatomic molecule (SAP-4.A, 3.B).

Part (c) consisted of two parts. Given a table of standard entropies of formation, students were asked to determine the standard entropy of reaction, $\Delta S°$, in part (c)(i). Using this calculated value, students were asked in part (c)(ii) to determine the standard Gibbs free energy of reaction, $\Delta G°$, using the provided value for the standard enthalpy of reaction, $\Delta H°$. Part (c)(i) was worth 2 points, and (c)(ii) was worth 1 point. In part (c)(i) the first point hinged on students using the given standard molar entropies and setting up the calculation of $\Delta S°$ using the correct reaction stoichiometry (ENE-4.B, 5.B). The second point was earned for the correct calculated value of $\Delta S°$ (ENE-4.B, 5.F). Part (c)(ii) asked students to use the value of $\Delta S°_{rxn}$ determined in part (c)(i), along with the provided value of $\Delta H°$ to calculate the $\Delta G°$ (ENE-4.C, 5.F).

In part (d) students were asked to interpret a particle drawing and calculate the partial pressure of CO at equilibrium based on the mole fraction of each component of the gas mixture and the total pressure of the mixture at equilibrium. (SAP-7.A, 5.D).

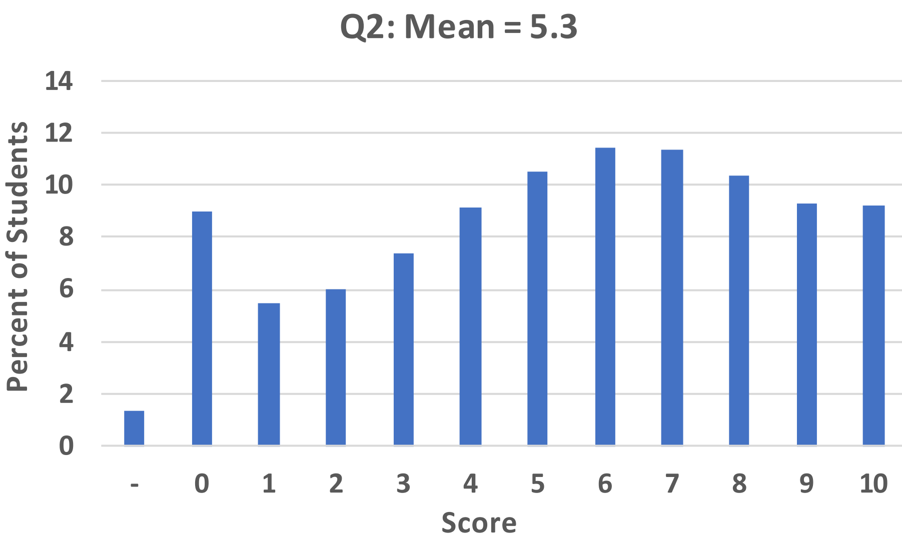
Part (e) asked students to write a K_p expression (TRA-7.B, 5.F) given a balanced gas-phase reaction.

Utilizing the K_p expression determined in part (e), students were provided the equilibrium partial pressure for all gas species and asked to calculate the value of K_p in part (f) (TRA-8.B, 5.C).

Part (g) was worth 2 points. Students were asked to make a claim about how the moles of the reactant gas will change when the volume of the system is doubled (TRA-8.B, 5.C) for the first point. The second point was then associated with the subsequent justification of their claim (TRA-8.B, 6.D).

How well did the responses 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 5.3 out of a possible 10 points, with a standard deviation of 3.1 points. The distribution of scores on this question is shown below.



In part (a) students had a difficult time accessing this point. Students earning the point were able to correctly identify the atom undergoing reduction and determine the oxidation number before and after the reduction process.

Roughly half of the students drew the correct Lewis structure for carbon monoxide in part (b).

The minority of students earned both points in part (c)(i). The first point in part (c)(i) (stoichiometry) was the more difficult of the two points to earn. Students earning just one of the two points recognized that the calculation of $\Delta S°$ involved subtracting the standard molar entropy of the reactants from the products. For part (c)(ii), the minority of students were able to successfully set up and correctly solve for $\Delta G°$ using $\Delta G° = \Delta H° - T\Delta S°$.

In part (d) approximately half of students correctly counted the number of particles for each of the three gases in the mixture and then divided the number of particles of CO by the total number of particles in the mixture.

Part (e) was the most accessible point on Question 2. Over half the students correctly wrote the K_p expression for the equilibrium system.

Roughly half of the students correctly inserted the partial pressures for each of the gases, provided in the table, into the K_p expression from part (e) to arrive at the correct value for K_p.

Over half of the students earned at least one of the two points in part (g). These students correctly predicted that the moles of CH_3OH would decrease (first point); however, students had difficulty justifying the claim (second point).

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) • The most common error was expressing oxidation states as a total from all like atoms in the molecule instead of as a property of individual atoms. For example, students would respond with an oxidation state +4 for H (CH_3OH, 4 H atoms in the molecule), rather than an oxidation state of +1.	Part (a) • Identifying hydrogen as being reduced and correctly communicating the oxidation state of hydrogen before and after the reaction.
Part (b) • A common misconception is that every atom in the Lewis structure must have 8 non-bonding electrons around it, resulting in structures with more valence electrons than permitted (16 or 12 instead of 10). • In some cases, students correctly included 10 valence electrons but violated the octet rule by drawing a carbon–oxygen double bond, with 2 non-bonding pairs of electrons on the oxygen atom and 1 non-bonding pair of electrons on the carbon.	Part (b) • Correctly completing the Lewis structure. :C≡O:
Part (c)(i) • The most common mistake made by students was not taking the reaction stoichiometry into account. • A less common error was reversing the setup of the calculation of $\Delta S°$ by using (reactants – products).	Part (c)(i) • Correctly setting up and calculating the value of $\Delta S°$. $\Delta S° = 198 + 2(131) - 240 = 220$ J/(K· mol_{rxn}).
Part (c)(ii) • The most common error was inconsistency in units: combining $\Delta H°$ in kJ/mol and $-T\Delta S°$ in J/mol.	Part (c)(ii) • Correctly setting up and calculating the value of $\Delta G°$. $\Delta G°$ = 90.0 kJ/mol_{rxn} – (375 K × 0.220 kJ/(K· mol_{rxn})) = +7.5 kJ/mol_{rxn}

Part (d) • The most common error was miscounting the number of gas phase particles of CO, H_2, and CH_3OH from the particle drawing. • Some students multiplied the number of CO particles by the total pressure in the container, forgetting to divide by the total number of particles first.	Part (d) • Determining that the mole fraction of CO in the gas sample is 0.30 and then multiplying the mole fraction by the total pressure (12 atm).
Part (e) • Students did not write the equilibrium expression in terms of partial pressure. • Students forgot to square the partial pressure of H_2 (the stoichiometric coefficient for H_2 in the balanced equation is 2). • Students erroneously included bracket notation in the expression, indicating the molar concentration of each component rather than its partial pressure.	Part (e) • $K_p = \frac{(P_{CO})(P_{H_2})^2}{(P_{CH_3OH})}$, the correct form of the equilibrium expression.
Part (f) • As with part (e), a common error was not squaring the partial pressure of H_2.	Part (f) • $K_p = \frac{(4.2\ atm)(8.4\ atm)^2}{(2.7\ atm)} = 110$
Part (g) • Missing the significance of Q relative to K. • Students would claim that moles of CH_3OH would decrease because $Q > K$, but then justify the claim by discussing how the reaction would re-establish equilibrium by producing more products. • Students used a Le Chatelier's argument without making a comparison between Q and K.	Part (g) • Students correctly claimed that the moles of CH_3OH would decrease. The students would then support this claim by arguing that when the volume doubles, the pressure will decrease by a factor of 2. Substituting half of the partial pressure values used in part (f), students would determine a value of Q (27) that is less than K_p. As equilibrium is re-established, the value of Q will increase to the value of K_p, which means that the system will shift toward the products and decrease the number of moles of CH_3OH.

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

1. Work with students on determining the oxidation state/number of an atom within molecular compounds and molecular ions.
2. Emphasize to students that the total number of electrons (bonding electrons + non-bonding electrons) represented in a Lewis structure must equate to the number of valence electrons contributed by each atom in the molecule.
3. Present students with more particle-level diagrams from which to deduce the properties of various systems.
4. Emphasize to students the accepted format to represent equilibrium expressions:
    a. To express the amount of a chemical species in terms of molarity, use brackets.
    b. To express gases in K_p expressions, use partial pressure notation (P_x) without brackets.
5. Clearly articulate the relationship between Q and K and the direction the chemical system will shift as equilibrium is re-established. Have students practice analyzing and predicting what happens in a variety of reaction systems where Q is different than K.

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

- Teachers can use AP Classroom to direct students to the AP Daily videos for Topics 2.5, 3.4, 4.7, 7.3, 7.4, 7.10, 9.2, and 9.3.
- Teachers can use AP Classroom to direct students to the 2022 AP Exam On-Demand Review Session 4: Equilibrium Multiple-Choice and Free-Response Questions and Session 8: Free-Response Question Medley.
- Teachers can assign topic questions and/or progress checks in AP Classroom to monitor student progress and identify areas that may need additional instruction or content and skill development.

Question 3

Task: Aluminum structure reactivity
Topics: Atomic structure, reactivity, particle-level representation, electrochemistry
Max Score: 10
Mean Score: 4.59

What were the responses to this question expected to demonstrate?

Question 3 deals with the atomic structure and reactions of aluminum. Part (a) began by asking students for the electron configuration of the aluminum atom (SAP-1.A, 3.B). Part (b) then asked students to explain why the Al^{3+} cation is smaller than the Al atom using principles of atomic structure (SAP-2.A, 6.C). Each part was worth 1 point.

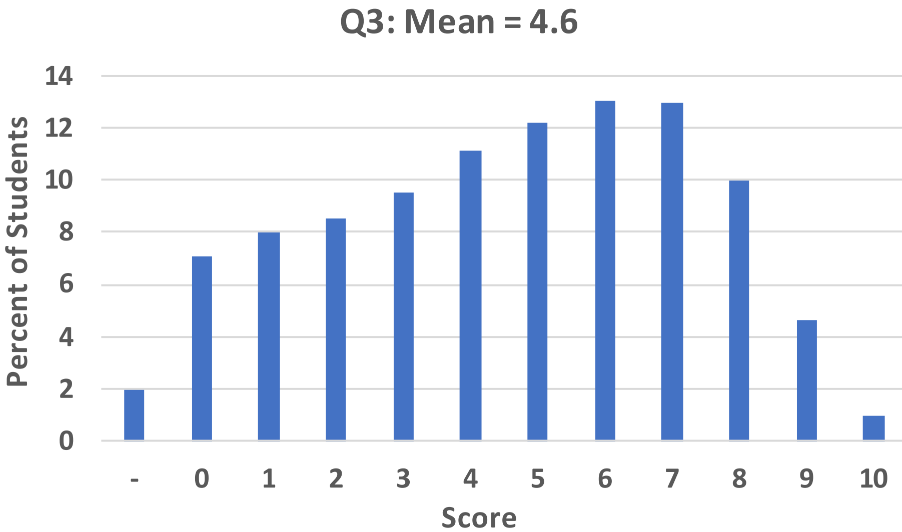
The question then turned to the analysis of the reaction between solid aluminum and silver ions. To prepare for the reaction, students were asked in part (c) to list the steps they would perform to make 200.0 mL of a $AgNO_3$ solution given the preweighed solid (SPQ-3.A, 2.C and 2.D) and a list of available equipment. Two points were possible for this procedure, the first for making a solution and the second for ensuring it contained a volume of 200.0 mL.

Students were then told that the solution was placed into a beaker containing aluminum and that a redox reaction occurred, producing solid silver and Al^{3+} ions. A particulate representation of the reactants was given, and students were asked to complete a particulate diagram in part (d) representing the species in the beaker after the reaction had occurred (TRA-1.C, 3.B; TRA-1.B, 3B; SAP-6.A, 3.C). Three points were possible for the particulate diagrams, as responses had to correctly show mass and charge balance between the diagrams and correct phases of matter for all species.

Parts (e), (f), and (g) were each worth 1 point and examined the thermodynamics of the reaction. In part (e) students were asked to calculate the value of $E°$ for the reaction from a given table of standard reduction potentials (ENE-5.A, 5.F). From the value of $E°$ calculated, students made a claim for the sign of $\Delta G°$ with justification (ENE-6.B, 5.C). Finally, students were asked to reason about the value of ΔG (or the driving force) of the reaction being positive, negative, or zero, after the reaction has been observed to stop progressing (ENE-6.C, 6.D).

How well did the responses 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 3 was 4.6 out of a possible 10 points, with a standard deviation of 2.7 points. The distribution of scores on this question is shown below.



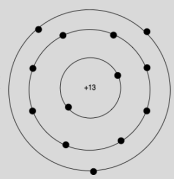
Part (a) was a very accessible entry point for students. Correct responses could list either the complete or noble gas electron configuration for the aluminum atom. Part (b) was more challenging, as many responses did not explicitly relate the difference in size between the species to the difference in energy levels of the electrons in Al and Al^{3+}. Many responses just stated a trend (more electrons will be larger) or invoked terminology (effective nuclear charge, electron shielding) without a clear discussion of the difference in the electronic structure of the two species. Some responses also incorrectly stated that cations have a different number of protons as compared to the neutral atom, leading to an incorrect conclusion.

Part (c) was challenging for students, as many responses used the incorrect glassware to attempt to prepare the volumetric 200.0 mL solution. In particular, many responses treated the volumetric flask as a graduated cylinder to pour 200.0 mL into another container to make the $AgNO_3$ solution. Also, many responses neglected to mention actually dissolving the solid, or they suggested adding the solid after filling the flask to the calibration mark.

Although most responses to part (d) showed the formation of Al^{3+} ions and elemental silver in the proper phases of matter, a variety of errors were seen. Responses either failed to maintain conservation of particles (mass) or did not use the stoichiometry of the balanced equation to correctly illustrate the products formed when two particles of Al would react, leading to inconsistent charge balance between the diagrams.

The final three parts of the question investigated the thermodynamics of the redox reaction represented in the particulate representation between solid aluminum and silver(I) cations. Students were extremely successful in determining the value of $E°$ for the reaction, making it a very accessible question. Incorrect responses included multiplying the $E°$ values by the stoichiometric coefficients of the reaction or trying to solve for $E°$ using a "products – reactants" algorithm. Most responses were successful in relating the value of $E°$ in part (e) to a negative value of $\Delta G°$ in part (f), utilizing the fact that a positive $E°$ indicates thermodynamic favorablity or explictly explaining that $\Delta G°$ would be negative via the realtionship $\Delta G° = -nFE°$. Incorrect responses more frequently stated a realtionship between $\Delta G°$ and $E°$ with no justification. Part (g) was challenging for students as many did not relate the fact that the reaction appeared to stop progressing as an indication of equiulibrium or the fact that the voltage, E, had dropped to 0. Incorrect responses would often state that $E°$ (and not E) became 0 when the reaction stopped progressing or made a general statement that nothing would change when the reaction stopped progressing, and hence ΔG would be 0.

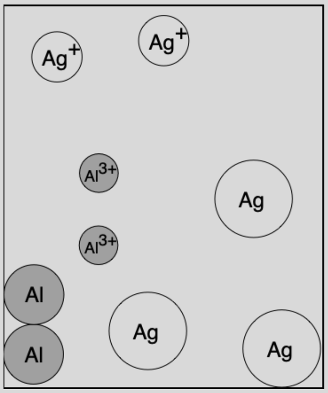
What common student misconceptions or gaps in knowledge were seen in the responses to this question?

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
Part (a) • Drawing a Lewis atom diagram:  • Drawing a “shell diagram”:  • Confusing the energy level with the number of electrons (e.g., $2s^1 2s^2 6p^2 1s^3 1p^3$).	Part (a) • Writing the electron configuration either in complete or noble gas format: $1s^2 2s^2 2p^6 3s^2 3p^1$ or $[Ne]3s^2 3p^1$.
Part (b) • Believing the the charge of 3+ in the aluminum cation means it has three more protons than Al, leading to greater attraction. • Using statements as opposed to principles of atomic structure: (e.g., cations are always smaller than neutral atoms; a species having more electrons always means that it is larger). • Vague justifications invoking *only* the terms electron shielding, electron repulsion, or effective nuclear charge without further elaboration or discussion of the locations of the electrons in respective energy levels. • A misunderstaning of Coulomb’s law, believing that the force of the nucleus is distrubuted over all the electrons in an element. Thus, Al’s electrons would experince less attraction than Al^{3+}’s because the force per electron would be less in the neutral atom.	Part (b) • The outermost electrons in Al are in the 3rd energy level, while the outermost electrons in Al^{3+} are in the 2nd energy level. Since the latter are in a lower energy level, the electrons in Al^{3+} will be closer to the nucleus, and the ion is smaller.

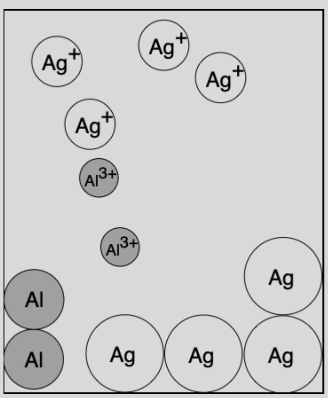
Part (c)	Part (c)
• Lack of understanding that the choice of glassware matters in the precision of the volume of the solution made (e.g., fill to the 200.0 mL mark in the 250 mL beaker). • Using the volumetric flask as a cylinder to deliver the volume of 200.00 mL to another container (e.g., fill the flask to the mark and then pour the water into the beaker containing the solid silver nitrate). • Lack of clarity or failure to describe that the silver nitrate needed to be dissolved during the solution making process (e.g., add silver nitrate to the flask and fill to the mark). • Adding the silver nitrate after filling the volumetric flask to the calibration mark. • Adding 200. mL of water from another container to the silver nitrate in the volumetric flask as opposed to filling to the calibration mark.	• Fill the volumetric flask with some water and then add the measured silver nitrate. Swirl to dissolve the solid and then dilute the solution with water to the 200.00 mL calibration mark (or line). Mix again.

Part (d)

- The diagram below does not satisfy conservation of atoms after the reaction occurs. The stoichiometry is done incorrectly, and the number of silver particles is not conserved from the original diagram.

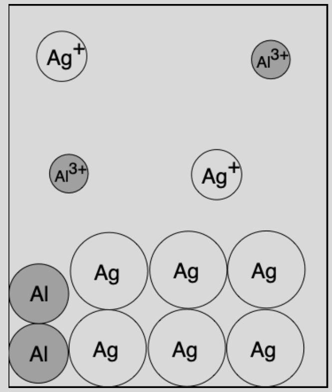


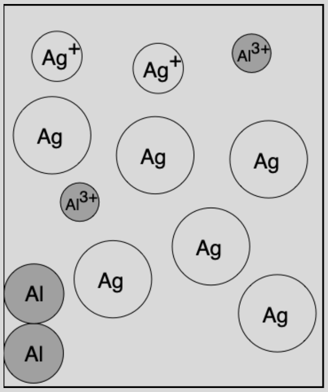
- The diagram below does not satisfy conservation of charge after the reaction occurs, as the stoichiometry is done incorrectly.



Part (d)

- The diagram below shows the correct amount of each product based upon the stoichiometry of the reaction with each species in the correct phase of matter.



• The diagram below does not correctly illustrate the correct state of matter for the products after the reaction occurs. 	
Part (e) • Attempting to calculate $E°$ using the $E°$ of the products (1.66) minus $E°$ of the reactants (0.80) (1.66 V – 0.80 V = 0.86 V). • Forgetting that $E°$ values are *intensive* properties that do not depend on the stoichiometric coefficents of the reaction. Hence, the following calculation is incorrect: 3(0.80 V) + 1.66 V = 4.06 V.	Part (e) • $E°$ = 0.80 V + 1.66 V = 2.46 V • $E° = E°_{red} - E°_{ox}$ = 0.80 V – (–1.66 V) = 2.46 V
Part (f) • Simply stating $\Delta G°$ is negative without justification in terms of thermodynamic favorablilty (as indicated by the value of $E°$) or through the mathematical relationship between $\Delta G°$ and $E°$. • Stating that $\Delta G°$ is positive for a thermodynamically favorable reaction.	Part (f) • Since $E°$ is positive, the reaction is thermodynamically favorable, and thus, $\Delta G°$ is negative. • Since $E°$ is positive and $\Delta G° = -nFE°$ (with n and F as positive constants), $\Delta G°$ is negative.

Part (g)	Part (g)
• Confusing the values of E and $E°$ and stating that the value of $E°$ is 0 at equilibrium. • Failing to recognize that because the $E°$ is large and positive, that equilibrium would occur when significant amounts of products were made, and not progressing any further would be indicitive of the equilibrium condition. • Misapplication of the expression $\Delta G° = -nFE°$ and setting $n = 0$ as if the reaction had stopped progressing.	• The value of ΔG is zero. The observation that the reaction stops progressing implies that E is 0. This indicates there is no longer a driving force for the reaction. • The value of ΔG is zero. The observation that the reaction stops progressing implies that equilibrium has been established, and ΔG is 0 at equilibrium.

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

1. Ensure that students are using correct notation when writing electron configurations.
2. When students are explaining values that depend upon atomic structure (size, ionization energy, likely charge of ions), ensure that they support their claim with specific information from the electron configuration of the species. Also, work with students so that they clearly understand the interactions between protons and electrons that underlie the ideas of electron shielding and effective nuclear charge so that these terms, if used, are done so in proper context. Note that any discussion about atomic structure can center on energy levels and/or Coulombic interactions without the need for those terms.
3. Allow students to consistently make solutions to understand proper procedure depending on the glassware needed. Students should also be able to explain why a certain vessel should be used to make a solution to meet demands the experiment places on the precision of the volume or concentration.
4. Practice multiple ways (written, particulate, and stoichiometric) for students to describe and to calculate with reactions.
5. Emphasize the intensive nature of $E°$ in calculations.

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

- Teachers can use AP Classroom to direct students to the AP Daily videos on Topics 1.5, 1.7, 1.8, 3.2, 3.7, 4.2, 4.3, 9.8, and 9.9.
- Teachers can use AP Classroom to direct students to the 2021 AP Exam On-Demand Review Session 4: Examining Coulomb's Law, Periodicity, & Intermolecular Forces and Session 7: Everything You Need to Know about Electrochemistry.
- To help students with improving the clarity and specificity of their written responses, teachers can use the "Write This, Not That – Updated 2019" compiled by Nora Walsh, available in the Resources Library of the Online Teacher Community.
- Teachers can assign topic questions and/or progress checks in AP Classroom to monitor student progress and identify areas that may need additional instruction or content and skill development.

Question 4

Task: Properties of NH_2Cl and NCl_3
Topics: Unit conversion, intermolecular forces and solubility, enthalpy
Max Score: 4
Mean Score: 1.42

What were the responses to this question expected to demonstrate?

Question 4 prompted students to perform various tasks concerning NH_2Cl and NCl_3 systems.

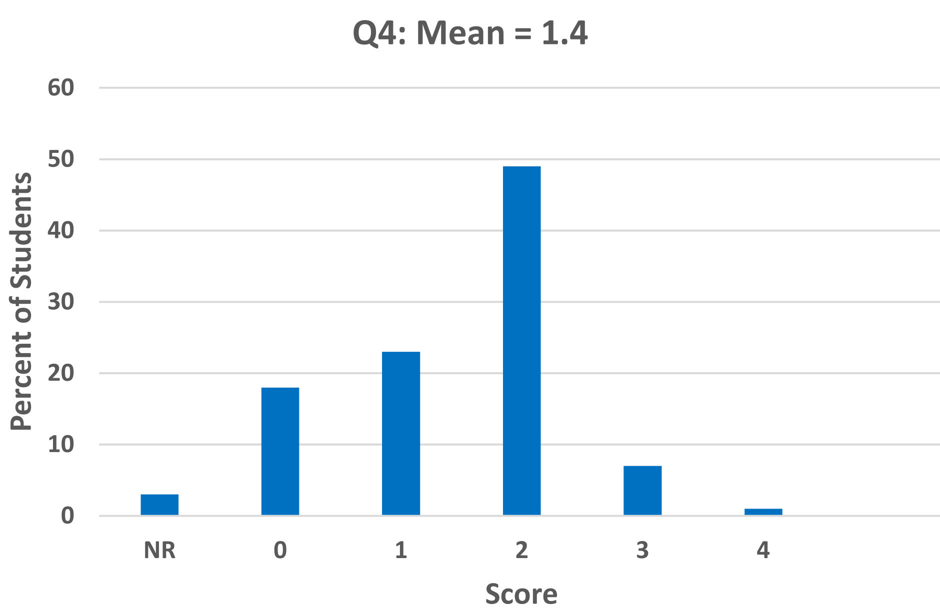
Part (a) asked students to perform a simple mathematical operation (Learning Objective SPQ-1.A, Science Practice 5.F from the *AP Chemistry Course and Exam Description*)—determining the moles of NH_2Cl in a volume of solution given the concentration of the solution (in units of g/L) and the molecular mass of the compound.

In part (b) students had the opportunity to earn 2 points. Students were asked to explain why NH_2Cl is very soluble in water, whereas NCl_3 is nearly insoluble. The explanation should identify the intermolecular interactions between water and both of the solutes (hydrogen bonding and dipole-dipole interactions) (SAP-5.A, 1.A). Students then had to compare the relative magnitudes of the intermolecular interactions between NH_2Cl/water and NCl_3/water to explain why NH_2Cl is more soluble (SPQ-3.C, 6.E).

Part (c) asked that students demonstrate mathematical skills by recognizing that moles of NCl_3 must be determined from the given mass, prior to determining the energy required to vaporize this sample (ENE-2.E, 5.F).

How well did the responses 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 1.4 out of a possible 4 points, with a standard deviation of 0.9 points. The distribution of scores on this question is shown below.



Part (a) was a very accessible point for students. Students correctly demonstrated their math skills to convert from units of concentration (g/L) to moles of NH_2Cl using the molar mass of the compound.

Part (b) was more of a challenge for students; the majority of students were successful at identifying the intermolecular forces between NH_2Cl and water, and between NCl_3 and water (this type of analysis could earn the first point). The greatest challenge for students was not recognizing the hydrogen bonding interaction that is present between the N atom in NCl_3 and water. Students had a higher success rate on the second point, correctly comparing the relative strengths of the identified intermolecular forces between the two molecules and water.

As with part (a), students were very successful in demonstrating their math skills in part (c). Students correctly determined the moles of NCl_3 present in the system and then calculated the heat required to vaporize the sample using the provided enthalpy of vaporization.

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 pay close attention to the units provided. A common incorrect response was 0.0016 mol, based on the given 0.0016 g/L.	Part (a) • Students set up the unit conversion correctly to arrive at a sample size of 3.1×10^{-5} moles.

Part (b)
 	
• A common error was that students did not clearly differentiate between bonds and intermolecular forces:
  ○ NH_2Cl has hydrogen bonds.
  ○ NH_2Cl has two N-H hydrogen bonds.
 	
• Another common error was not focusing on the difference in the number of hydrogen bonding sites in NH_2Cl and NCl_3:
  ○ NH_2Cl and H_2O are polar, so "like dissolves like" and NH_2Cl dissolves in water.
  ○ Students did not recognize that the non-bonding pair of electrons on the nitrogen atom in NCl_3 can participate in hydrogen
	Part (b)
	
	• Students clearly differentiating between bonds and intermolecular forces:
	  ○ NH_2Cl can form intermolecular hydrogen bonds with water.
	  ○ The H atom bonded to the nitrogen atom in NH_2Cl can form a hydrogen bond with the O atom in water.
	
	• Students noted the difference in the number of hydrogen bonding sites in NH_2Cl and NCl_3:
	  ○ NH_2Cl can form more hydrogen bonds with water, which explains its higher solubility.
	  ○ NCl_3 can only form one hydrogen bond with a water molecule, while NH_2Cl can form three hydrogen bonds with three different water molecules, making NH_2Cl more soluble.

bonding with a different molecular compound (water in this instance). • A third common error was incorrectly stating that bonds were broken, or ions were formed: ○ When NH_2Cl dissolves, bonds are broken. ○ NH_2Cl dissociates into ions when added to water. ○ Using the word "bond" without a modifier. • Finally, students would often fail to address the prompt by not focusing on the interactions between each solute and the solvent (water): ○ Students would identify and discuss the type and magnitude of the intermolecular forces between the two solutes, rather than the intermolecular forces acting between solute and solvent particles. ○ Students discussed the intermolecular forces in a pure sample of the solute, and not the interactions between the solute and the water solvent.	• Students recognized the hydrogen bonding interactions between NH_2Cl and water: ○ When NH_2Cl dissolves, new hydrogen bonds are formed between NH_2Cl and water.
Part (c) ○ A common error was that students performed the mathematical calculation correctly but included units of moles in their answer: 4.10 kJ/mol.	Part (c) ○ Students performed the mathematical calculations correctly and reported an energy value in the correct units.

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

1. Emphasize to students that the hydrogen bond is a weak electrostatic interaction between covalent molecules with certain features.
    a. Many responses indicated that NH_2Cl has hydrogen bonding, when a much clearer response would be to indicate that NH_2Cl can form hydrogen bonds <u>between</u> its molecules and water molecules.
    b. Describe the attractive intermolecular force between a solute molecule and a water molecule as a hydrogen bonding interaction. For example, "The H atom covalently bonded to the nitrogen atom in NH_2Cl can form a hydrogen bond with the O atom in water."

c. Talk about hydrogen bonding in terms of hydrogen bond acceptors and hydrogen bond donors and give examples of each. For example, NCl_3 is a hydrogen bond acceptor, which explains why it can form hydrogen bonds with water molecules. However, NCl_3 cannot form intermolecular hydrogen bonds with itself because it is not a hydrogen bond donor. NH_2Cl is a hydrogen bond donor and acceptor; NH_2Cl can form intermolecular hydrogen bonds with itself and also with water.

2. Solutions are frequently discussed following a discussion of intermolecular attractive forces and provide an excellent opportunity to revisit these forces in the context of a mixture of a solute and solvent.
    a. During the solution discussion, mention that hydrogen bonding interaction can occur where one of the molecules engaged in the interaction does not form hydrogen bonds in its pure state (NCl_3).
    b. The nitrogen atom in NCl_3 does have a lone pair of electrons capable of interacting with a hydrogen atom covalently bonded to a N, O, or F atom in another compound. The majority of students did not include this possibility in their response.

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

- Teachers can use AP Classroom to direct students to the AP Daily videos on Topics 3.1, 3.2, 3.10, and 6.5.
- Teachers can use AP Classroom to direct students to the 2021 AP Exam On-Demand Review Session 4: Examining Coulomb’s Law, Periodicity, & Intermolecular Forces and 2022 AP Exam On-Demand Review Session 7: Bonding and Condensed State.
- To help students with improving the clarity and specificity of their written responses, teachers can use the “Write This, Not That – Updated 2019” compiled by Nora Walsh, available in the Resources Library of the Online Teacher Community.
- Teachers can assign topic questions and/or progress checks in AP Classroom to monitor student progress and identify areas that may need additional instruction or content and skill development.

Question 5

Task: Analysis of N_2O_5 kinetics
Topics: Rate laws, reaction mechanisms, temperature-dependence of rate constant
Max Score: 4
Mean Score: 1.32

What were the responses to this question expected to demonstrate?

Question 5 prompted students to analyze the kinetic properties of the decomposition of N_2O_5.

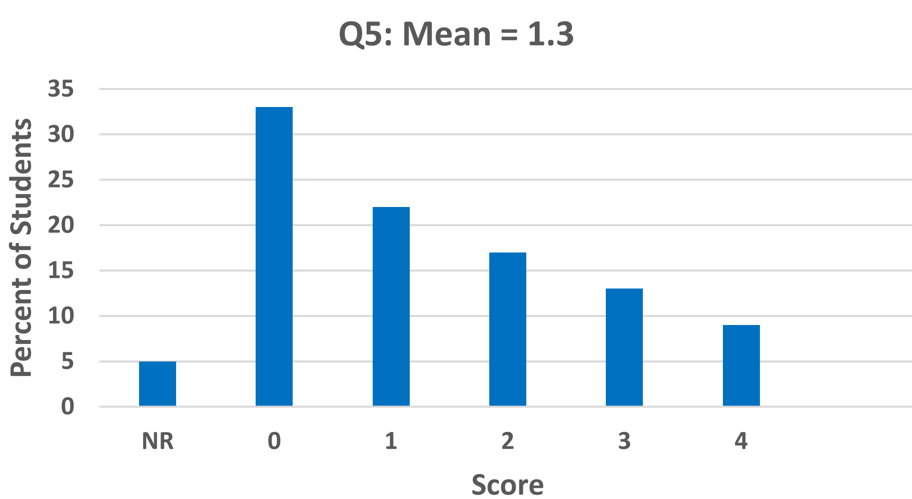
In part (a) students were to demonstrate their understanding of the relationship between the change in concentration as a function of time by determining the value of the rate constant (Learning Objective TRA-3.B, Science Practice 5.F from the *AP Chemistry Course and Exam Description*). Part (a) was worth 2 points: the first point for the correct determination for the value of the rate constant and the second point for the correct units of the rate constant.

Part (b) provided students with a proposed three-step mechanism for the decomposition of N_2O_5. From this information, students were to determine which step of the mechanism is the rate-determining step, based on the provided rate law equation (TRA-3.B, 5.F).

In part (c) students were asked to predict, and then justify, the dependence of the rate constant on a change in the initial concentration of N_2O_5 at constant temperature (TRA-4.B, 2.F).

How well did the responses 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 1.3 out of a possible 4 points, with a standard deviation of 1.3 points. The distribution of scores on this question is shown below.



In general terms, this question was accessible to students, with very few responses off topic or left blank.

In part (a) responses that recognized the first-order behavior from the data table (constant half-life) could determine the correct value of the rate constant, k, using either the half-life equation or the integrated first-order rate law equation from the equation sheet. The correct value required a correct calculation from one of these equations that earned 1 point, and the correct units required an algebraic analysis of the units in either equation that earned a second point.

In part (b) responses that correctly selected Step 1 as the rate-determining step with a valid justification earned the point.

In part (c) correct student responses claimed that the rate constant, k, would remain the same with a valid justification that either addressed that k is independent of a change in concentration, or that k is only dependent upon the temperature at which the reaction was carried out.

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) • A very common error for students who solved for the correct value of k based on a correct inference of a first-order reaction was neglecting to include units (hr^{-1}) in the answer or using units that did not agree with the data in the table (s^{-1} or min^{-1}). • Another common student error was to make an incorrect assumption about the order of the reaction that was not consistent with the data provided. Students could still earn the second point if their work and units were consistent with their erroneous assumption: ○ Zero-order assumption: $k = ([N_2O_5]_0 - [N_2O_5]_t)/(t) =$ $(0.160\ M - 0.0200\ M)/(5.00\ \text{hr}) = 0.028\ M/\text{hr}$ ○ Second-order assumption: $k = (1/[N_2O_5]_t - 1/[N_2O_5]_0)/(t) =$ $(1/0.0200\ M - 1/0.160\ M)/(5.00\ \text{hr})$ $= 8.75\ M^{-1}\ \text{hr}^{-1}$	Part (a) • Successful students identified the process as first-order, and used a variety of methods to derive the value of the rate constant, and included appropriate units in their answers: ○ First-order calculation: The reaction is first order. Therefore, $k = (\ln[N_2O_5]_0 - \ln[N_2O_5]_t)/(t) =$ $(\ln(0.160\ M) - \ln(0.0200\ M))/(5.00\ \text{hr})$ $= 0.416\ \text{hr}^{-1}$ ○ Half-life calculation: The reaction is first order with a half-life of 1.67 hr. Therefore, $k = (\ln 2)/t_{1/2} = (0.693)/1.67\ \text{hr} = 0.415\ \text{hr}^{-1}$ ○ Other units: If converted correctly, students could earn the second point with units other than hr^{-1}: $0.00693\ min^{-1}$, $1.16 \times 10^{-4}\ s^{-1}$, etc.

Part (b) • Common errors were incomplete or inaccurate statements about why Step 1 was the rate-limiting step: ○ Step 1 because N_2O_5 is a reactant. ○ Step 1 because it is the first step. ○ Step 1 because it is the only step in which the intermediates don't cancel out.	Part (b) • Successful students correctly related the unimolecular first step of the mechanism to the overall rate law of the reaction: ○ Step 1 because N_2O_5 is the only reactant. ○ Step 1 because its rate law matches the given rate law. ○ Step 1 because it is unimolecular as required by the given rate law.
Part (c) • Student errors included a variety of incorrect relationships between *k* and the effect of concentration on the rate: ○ *k* remains the same because when the initial concentration is doubled, the rate remains the same. ○ *k* remains the same because it is a first-order reaction. ○ *k* remains the same because the time it takes for the reaction to reach completion is also doubled. • Another error was confusing the rate constant, *k*, with the equilibrium constant, *K*: ○ *K* remains the same because only *Q* changes, and the reaction is driven to the right. *K* is constant at constant temperature.	Part (c) • Successful students gave correct reasons for why *k* remains the same: ○ *k* remains the same because when the initial concentration is doubled, the rate also doubles, and in the first-order equation the factor of 2 cancels. ○ *k* remains the same because it is independent of concentration. ○ *k* remains the same because it is only a function of temperature, and temperature is constant. ○ *k* remains the same because it only depends on half-life for a first-order reaction, which is constant at the same temperature.

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

1. Some students seemed comfortable solving equations but didn't actually understand what the results meant. Perhaps a balanced quantitative/qualitative approach to the study of kinetics would be helpful.
2. Many students were confused about the conceptual difference between the rate of the reaction and the rate constant, k. Providing examples of multiple trials of the same reaction where students can calculate the same value of k for trials with different rates may help students understand the difference. Following up with data from the same reaction at a different temperature can provide the starting point for a discussion about the temperature dependence of k.
3. To keep track of the units in a multistep calculation, encourage students to include units in each step of their calculation setup and apply dimensional analysis in the intermediate calculations.

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

- Teachers can use AP Classroom to direct students to the AP Daily videos for Topics 5.2, 5.3, 5.4, 5.7, and 5.8.
- Teachers can use AP Classroom to direct students to the 2022 AP Exam On-Demand Review Session 2: Kinetics Multiple-Choice and Free-Response Questions and the 2021 Session 8: Free-Response Question Medley & Exam Strategies, particularly the Kinetics section that begins at 33:30.
- Teachers can assign topic questions and/or progress checks in AP Classroom to monitor student progress and identify areas that may need additional instruction or content and skill development.

Question 6

Task: Experimental $KMnO_4$ colorimetry
Topics: Graphical analysis, dilution, error analysis
Max Score: 4
Mean Score: 1.97

What were the responses to this question expected to demonstrate?

Question 6 presented students with a laboratory experiment to determine the permanganate concentration in a solution by colorimetry/spectrophotometry.

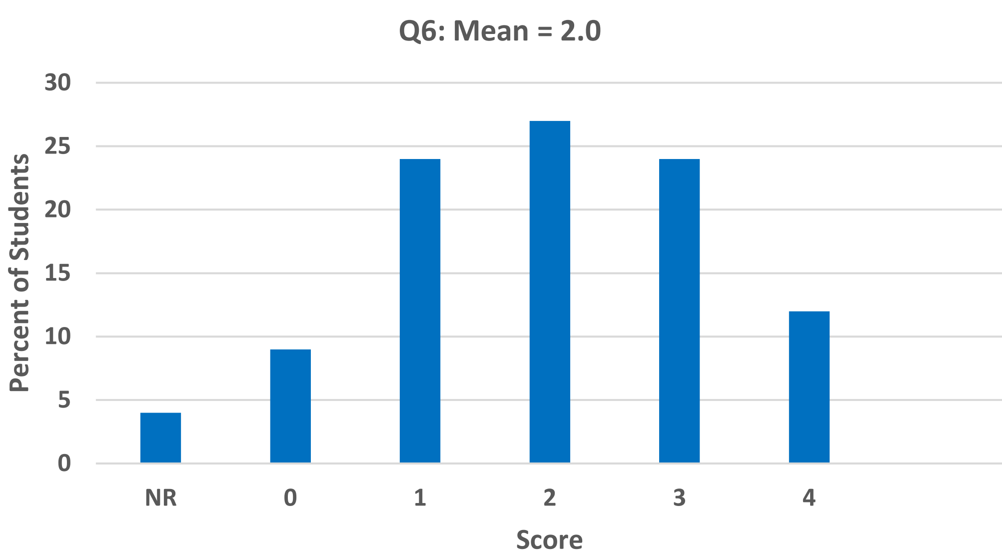
Part (a) asked students to identify the optimum wavelength for the experiment by analyzing a plot of absorbance versus wavelength (Learning Objective SAP-8.C, Science Practice 6.A from the *AP Chemistry Course and Exam Description*).

Part (b) was worth 2 points. Part (b)(i) asked students to determine the volume of stock solution in a graduated cylinder and estimate the volume reading appropriately to the nearest 0.1 mL (SPQ-3.A, 2.D). Part (b)(ii) asked students to calculate the volume of a stock solution required to perform a dilution resulting in the desired standard concentration (SPQ-3.A, 5.F).

Part (c) provided students with an experimental procedure to produce a calibration curve as well as an experimental calibration curve with a marked point below the line of best fit. The prompt then asked students to identify a step in the procedure that could have been executed incorrectly to produce the marked data point and to justify their answer (SAP-8.C, 2.E).

How well did the responses 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 2.0 out of a possible 4 points, with a standard deviation of 1.2 points. The distribution of scores on this question is shown below.



Part (a) was a very accessible point with the vast majority of students earning the point. Responses demonstrated a strong ability to recognize that the wavelength associated with the maximum absorbance would correspond to the optimum wavelength and to read this wavelength from the spectrum provided.

Less than half of the responses earned the point for part (b)(i) for correctly reading the graduated cylinder and estimating the volume to 0.1 mL and reporting a volume of 92.0 mL. In part (b)(ii), most students were able to substitute into $M_1V_1 = M_2V_2$ and correctly calculate the volume of stock solution required.

Part (c) was the most challenging point for students. Responses generally reflected an understanding that the data point below the line of best fit was likely the result of a lower concentration sample due to dilution with some distilled water. However, students had a difficult time connecting the lower concentration to the procedural step that was not executed correctly (Step 3).

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) • While most students earned this point, those that did not earn the point commonly reported a large range of wavelengths instead of the optimum wavelength.	Part (a) • 525 nm
Part (b)(i) • A common misconception was to report the volume to 1 mL precision. A graduated cylinder with increments every mL should have a reported volume to 0.1 mL precision. • Another common error was to report 90.2 mL, reading the increments as 0.1 mL instead of 1.0 mL.	Part (b)(i) • 92.0 mL
Part (b)(ii) • A common skill gap was to begin with $M_1V_1 = M_2V_2$ and report the volume as 143 mL, demonstrating both an inability to rearrange the equation correctly (inverting), as well as a misconception of the dilution process given that it is not possible to dilute 143 mL of stock solution to a final volume of 100.0 mL.	Part (b)(ii) • $M_1V_1 = M_2V_2$ $V_1 = M_2V_2/M_1$ $V_1 = (1.68 \times 10^{-3}\ M)(100.0\ \text{mL})/(2.40 \times 10^{-3}\ M) = 70.0\ \text{mL}$

Part (c)	Part (c)
• A common misconception was failing to recognize that rinsing with standard solution as described in step 3 of the procedure would remove any distilled water left over from rinsing in step 2.	• The student forgot to rinse the cuvette with standard solution in step 3. This means that any leftover distilled water from step 2 would dilute the standard solution and result in a lower absorbance.

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

1. Present students with a variety of measuring tools (rulers, tape measures, thermometers, graduated cylinders) to discuss the concept of precision and how to scientifically obtain measured values from these tools. Compare and contrast the different levels of precision offered by different tools.
2. Offer students various scenarios involving error analysis. In the Question 6 scenario, students had to identify the step at which the error occurred and explain their answer.
3. Provide students with an experimental procedure and have them hypothesize how an error for each step could arise and how it would affect the final outcome of the experiment. (e.g., Why is the amount of precipitate lower/higher than expected?)

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

- Teachers can use AP Classroom to direct students to the AP Daily videos for Topics 3.7 and 3.13.
- Teachers can use AP Classroom to direct students to the 2021 AP Exam On-Demand Review Session 3: Experiment-Based Free-Response: Calorimetry & Beer's Law.
- Teachers can use online simulators like ChemCollective – Qualitative and Quantitative Analysis of Food Dye and PhET – Beer's Law Lab to build student skill and understanding prior to conducting an experiment similar to Investigations 1 and 2 in the *AP Chemistry Guided Inquiry Experiments* (available in the Overview section of the Course Resources in AP Classroom). Teachers can also engage students in building their own spectrophotometer using a Smartphone using the information in this article on ChemEd X.
- Teachers can assign topic questions and/or progress checks in AP Classroom to monitor student progress and identify areas that may need additional instruction or content and skill development.

Question 7

Task: Silver oxalate solubility
Topics: Hybridization, K_{sp} equilibrium expression and molar solubility, solubility in an acidic environment
Max Score: 4
Mean Score: 1.05

What were the responses to this question expected to demonstrate?

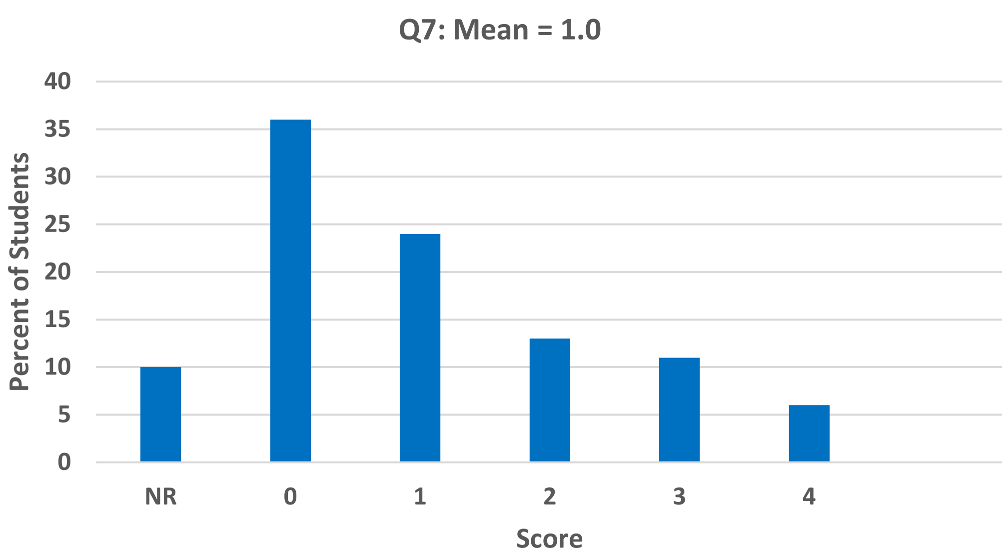
Question 7 prompted students to analyze solubility properties of $Ag_2C_2O_4$.

Part (a) asked the students to identify the hybridization of either carbon atom in the oxalate ion (Learning Objective SAP-4.C, Science Practice 1.A from the *AP Chemistry Course and Exam Description*).

Part (b) offered students the opportunity to earn 3 points. For part (b)(i), the students were asked to write the K_{sp} expression for the dissolution of $Ag_2C_2O_4$ (SPQ-5.A, 5.B). Based on the equilibrium expression, part (b)(ii) had the students calculate the molar solubility of $Ag_2C_2O_4$ given the K_{sp} value (SPQ-5.A, 5.F). Part (b)(iii) asked students to write the net-ionic equation that explained why the solubility of $Ag_2C_2O_4$ increased after the addition of a strong acid to the solution (SPQ-5.C, 6.D).

How well did the responses 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 1.0 out of a possible 4 points, with a standard deviation of 1.2 points. The distribution of scores on this question is shown below.



Part (a) was the most accessible point on this question. The students demonstrated that they were able to analyze the given structure for the molecular ion and determine the hybridization of an atom in that ion.

In part (b)(i) the students demonstrated that they were able to correctly write the equilibrium expression for the solubility product constant for a compound, given only the chemical formula for that compound.

In part (b)(ii) the students were then able to use the equilibrium expression from part (b)(i), along with the stoichiometric relationships of the ions, to determine the molar solubility of the compound.

Part (b)(iii) was the most challenging section of this question. Those students who successfully earned this point responded with the correct ionic equation that explained why the solid silver oxalate was more soluble in an acidic environment.

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 mistakenly wrote the electron configuration for carbon: $1s^2 2s^2 2p^2$. • Students applied VSEPR theory and described the geometry in their response (trigonal planar) rather than discussing hybridization.	Part (a) • sp^2
Part (b)(i) • There were several common knowledge gaps demonstrated when students reported the equilibrium expression: ○ $K_{sp} = [Ag^+][C_2O_4^{2-}]$ (wrong exponent on silver ion) ○ $K_{sp} = [Ag^{2+}][C_2O_4^{2-}]$ (wrong charge for silver ion) ○ $K_{sp} = [Ag^+]^2[C_2O_4^-]$ (wrong charge for oxalate ion) ○ $K_{sp} = [Ag]^2[C_2O_4]$ (no charges on ions)	Part (b)(i) • Successful students used the ion charges and the correct exponents for each ion: ○ $K_{sp} = [Ag^+]^2[C_2O_4^{2-}]$

Part (b)(ii) • Incorrectly setting up the mathematical equilibrium expression to solve for the molar solubility, or incorrectly solving for the variable(s). ○ Wrong setup: If $K_{sp} = s^3$, then $s = 1.75 \times 10^{-4}$ If $K_{sp} = 2s^3$, then $s = 1.39 \times 10^{-4}$ ○ Incorrect Algebra: If $K_{sp} = (5.4 \times 10^{-12})^3 \div 4$, then $s = 4.39 \times 10^{-5}$ If $K_{sp} = (5.4 \times 10^{-12} \times 4)^3$, then $s = 2.78 \times 10^{-4}$ If $K_{sp} = (5.4 \times 10^{-12} \div 4)$, then $s = 1.16 \times 10^{-6}$	Part (b)(ii) • Successful students expressed the correct relationship between K_{sp} and the molar solubility, s, and solved for the molar solubility. ○ $5.4 \times 10^{-12} = 4s^3$, $s = 1.11 \times 10^{-4}\ M$
Part (b)(iii) • There were several common misconceptions that students demonstrated when writing the net-ionic equation. ○ $2\ HClO_4 + AgC_2O_4 \rightarrow H_2C_2O_4 + 2\ AgClO_4$ (the equation is not a net-ionic equation) ○ $2\ H^+ + ClO_4^- + C_2O_4^{2-} \rightarrow H_2C_2O_4$ (the equation includes a spectator ion) ○ $H^+ + ClO_4^- + C_2O_4^{2-} \rightarrow H_2C_2O_4$ (the equation is not balanced)	Part (b)(iii) • The net-ionic equation for the reaction between H^+ and oxalate ions: ○ $2\ H^+ + C_2O_4^{2-} \rightarrow H_2C_2O_4$ ○ $H^+ + C_2O_4^{2-} \rightarrow HC_2O_4^-$ • The net-ionic equation for the reaction between H_3O^+ ions and oxalate ions: ○ $2\ H_3O^+ + C_2O_4^{2-} \rightarrow H_2C_2O_4 + 2\ H_2O$ ○ $H_3O^+ + C_2O_4^{2-} \rightarrow HC_2O_4^- + H_2O$

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

1. Solubility-constant expressions
    a. Provide students with a set of insoluble salts and have students write the dissociation reactions for each compound, focusing on balancing the reaction in terms of both mass (stoichiometry) AND charge (net charge of the product ions must be neutral for the dissociation of insoluble salts).
    For example, $Al(OH)_3(s) \rightarrow Al^{3+}(aq) + 3\ OH^-(aq)$
    b. Emphasize to students that the stoichiometric coefficients play a major role in correctly setting up the K_{sp} expression in order to determine molar solubility. Every coefficient is both a multiplicative factor and an exponential term on the same ion. From the previous example, $K_{sp} = (s)(3s)^3$.
2. Emphasize that net-ionic equations only illustrate those chemical species that undergo chemical change, and that reactants and products must be mass and charge balanced.

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

- Teachers can use AP Classroom to direct students to the AP Daily videos on Topics 2.7, 7.11, 7.12, and 7.13.
- Teachers can use AP Classroom to direct students to the 2022 AP Exam On-Demand Review Session 3: *Ksp*, Q_{sp}, and Solubility and Session 4: Equilibrium Multiple-Choice and Free-Response Questions.
- Teachers can use the PhET simulation—Salts & Solubility—and several accompanying Teacher-Submitted Activities to connect particle-level views to calculations of solubility and K_{sp}.
- Teachers can assign topic questions and/or progress checks in AP Classroom to monitor student progress and identify areas that may need additional instruction or content and skill development.