



Chief Reader Report on Student Responses: 2023 AP[®] Chemistry Free-Response Questions

• Number of Students Scored	139,448		
• Number of Readers	460		
• Score Distribution	Exam Score	N	%At
	5	22,379	16.05
	4	37,791	27.10
	3	44,568	31.96
	2	23,540	16.88
	1	11,170	8.01
• Global Mean	3.26		

The following comments on the 2023 free-response questions for AP[®] Chemistry were written by the Chief Reader, Kyle A. Beran, 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: Mn salt and Mn battery

Topic: Aufbau principle, empirical formula, experimental error, electrochemistry, Gibbs free energy

Max Score: 10

Mean Score: 5.38

What were the responses to this question expected to demonstrate?

Question 1 presented students with a variety of chemical situations involving manganese and its compounds.

Part (a)(i) required students to provide an electron configuration for the transition element manganese. The intent was for students to demonstrate understanding of the Aufbau principle using an appropriate representation for electron configuration (Learning Objective SAP-1.A, Skill 3.B from the *AP Chemistry Course and Exam Description*).

Part (a)(ii) required students to use the electron configuration determined in (a)(i) to identify which subshell loses electrons first when manganese atoms form cations. The intent was for students to demonstrate understanding of ion formation from the electronic structure of an atom (SAP-2.A, 4.A).

Parts (b), (c), (d), and (e) involved a chemical equation with unknown subscripts “x” and “y” for the formation of a Mn_xCl_y compound from the reaction between $\text{Mn}(s)$ and $\text{HCl}(aq)$. Students were given a set of experimental data to analyze, which contains the mass of an empty beaker, the mass of the empty beaker and $\text{Mn}(s)$, and the mass of beaker and $\text{Mn}_x\text{Cl}_y(s)$ heated to constant mass.

Part (b) required students to calculate the mass of Cl in the dry Mn_xCl_y sample that remains in the beaker. The intent of the question was for students to use the experimental data provided to find the mass of Cl (SPQ-1.A, 5.F).

Part (c) required students to calculate the moles of Cl based on the mass of Cl determined in part (b) (SPQ-1.A, 5.F).

Part (d) required students to determine the empirical formula of the Mn_xCl_y sample using the moles of Cl determined in part (c) and a given quantity of moles of Mn (SPQ-2.A, 3.B).

Part (e) required students to explain how the moles of Cl calculated in part (c) would be affected in the event of an experimental error where a portion of the Mn_xCl_y splattered out of the beaker during the process of heating the product to dryness (SPQ-2.A, 6.G).

Part (f) of this question consisted of four parts that revolve around an alkaline battery containing MnO_2 . Students were provided with a table containing three reduction half-reactions and the accompanying standard reduction potentials. One half-reaction contains MnO_2 , and the other two half-reactions contain Zn.

Part (f)(i) required students to use the half-reactions given in the table to write the balanced net ionic equation representing the most thermodynamically favorable reaction (ENE-6.A, 5.E).

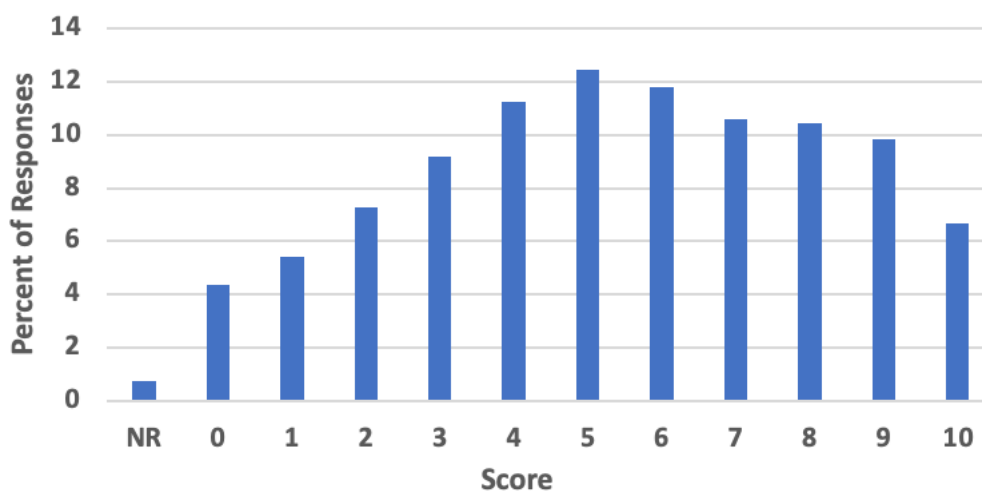
Part (f)(ii) required students to calculate the standard cell potential (E°_{cell}) for the overall reaction occurring in the battery (ENE-6.A, 5.F).

Part (f)(iii) required students to calculate the change in Gibbs free energy (ΔG°_{rxn}) for the reaction in part (f)(i), in units of kJ/mol_{rxn} , utilizing the mathematical relationship between ΔG°_{rxn} and E°_{cell} (ENE-6.B, 5.F).

Part (f)(iv) required students to evaluate a claim (agree or disagree and then provide a justification) that the total mass of the battery, a closed system, decreases during operation (ENE-6.A, 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 1 was 5.38 out of a possible 10 points, with a standard deviation of 2.80 points. The distribution of scores on this question is shown below.



Part (a)(i) was a very accessible point for the majority of students. Student responses successfully provided a correct representation of the electron configuration for Mn using the Aufbau principle. Correct representations included either the long-hand electron configuration (seen most of the time) or the electron configuration that used the noble gas abbreviation.

Part (a)(ii) was a very accessible point for the majority of students as well. Student responses successfully provided the correct identification of the subshell from which electrons were lost in the formation of the Mn^{2+} cation, consistent with the electron configuration written in part (a)(i).

Part (b) was also a very accessible point for the majority of students. Student responses successfully selected the appropriate experimental data and followed a logical computational pathway to calculate the mass of Cl in the solid Mn_xCl_y product.

Part (c) was a very accessible point for the majority of students. Student responses successfully converted grams of Cl from part (b) into moles of Cl using dimensional analysis and the mole concept by following a logical computational pathway.

Part (d) was somewhat less accessible point for students. Some student responses successfully used the given moles of Mn and the moles of Cl from part (c) to find the quantitative relationship between elemental composition and empirical formula.

Part (e) was a moderately accessible point for students with a slight majority successfully explaining how the splattering of Mn_xCl_y while heating to dryness would lead to a decrease in the calculated moles of Cl.

Part (f)(i) was the most challenging point for students to earn. Students who did earn the point were able to successfully determine the balanced net ionic equation by choosing and correctly adding the two half-reactions for the electrochemical cell that would produce the most thermodynamically favorable overall reaction.

Part (f)(ii) was also a fairly challenging point for students to earn. Students who did earn the point were able to follow a logical computational pathway using the half-cell reduction potentials from the table to correctly calculate the E°_{cell} that corresponded to the most thermodynamically favorable overall reaction. Students who had an incorrect net ionic equation in (f)(i) could still earn the point for (f)(ii) if they calculated an E°_{cell} that is consistent with the equation in (f)(i).

Part (f)(iii) was also a fairly challenging point for students to earn. Students who did earn the point were able to follow a logical computational pathway using the E°_{cell} from part (f)(ii) to calculate $\Delta G^\circ_{\text{rxn}}$, using $n = 2$ electrons. Students who had an incorrect net ionic equation in (f)(i) could still earn the point by using the E°_{cell} from part (f)(ii) to calculate $\Delta G^\circ_{\text{rxn}}$, using a value for n (moles of electrons) that was consistent with their half-reaction work explicitly shown in part (f)(i). Students who earned the point this way most commonly used $n = 4$, which was usually connected to using all three half-reactions in part (f)(i).

Part (f)(iv) was a moderately challenging point for students to earn. Many student responses correctly disagreed with the claim that the battery mass was decreasing because the anode was losing mass. However, to earn the point, the justification had to address the fact that mass may be lost from one side (the anode or cathode) but that an equal mass is gained by the other side, so the total mass remains the same. While this was the most common justification seen, other justifications that earned the point included the following:

- The battery is an enclosed system; therefore, the total mass remains constant.
- All reactants and products are solids (no gases), so nothing escapes or enters the battery.
- The anode gains mass instead of losing mass because Zn is oxidized to ZnO. The point was awarded here for correctly using and explaining the chemistry occurring at one of the electrodes in the electrochemical cell as a justification.

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

<i>Common Misconceptions/Knowledge Gaps</i>	<i>Responses that Demonstrate Understanding</i>
<p>Part (a)(i)</p> <ul style="list-style-type: none"> The most common error concerned skipping one or more subshells (e.g., $1s^2 2s^2 2p^6 3s^2 3p^6 3d^5$), or mislabeling the last subshell (e.g., $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 4d^5$). On occasion, students would provide an electron orbital diagram instead of an electron configuration. 	<p>Part (a)(i)</p> <ul style="list-style-type: none"> $[Ar] 3d^5 4s^2$ $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^5$ $1s^2 2s^2 2p^6 3s^2 3p^6 3d^5 4s^2$ An orbital diagram correctly showing the location of electrons in properly labeled subshells and orbitals that demonstrates understanding of electron location.
<p>Part (a)(ii)</p> <ul style="list-style-type: none"> The most common error was having a correct electron configuration but then choosing 3d as the subshell from which the electrons were lost first. Students frequently demonstrated a misconception that electrons are always lost from the last subshell in the electron configuration. 	<p>Part (a)(ii)</p> <ul style="list-style-type: none"> 4s or $4s^2$ For an incorrect (a)(i) such as $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 4d^5$, the point in (a)(ii) would be earned for a response of 4d, which is consistent with the incorrect electron configuration and demonstrates understanding that electrons are lost from the outermost subshell.
<p>Part (b)</p> <ul style="list-style-type: none"> The most common error here was often subtracting the total mass from the empty beaker and indicating that was the mass of Cl. If this was done, and the mistake was carried forward, the student could earn points in parts (c) and (d) if they are consistent with the answer in part (b). 	<p>Part (b)</p> <ul style="list-style-type: none"> $62.673 \text{ g} - 61.262 \text{ g} = 1.411 \text{ g Cl}$ $62.673 \text{ g} - 60.169 \text{ g} = 2.504 \text{ g total dry mass}$ $61.262 \text{ g} - 60.169 \text{ g} = 1.093 \text{ g Mn}$ $2.504 \text{ g} - 1.093 \text{ g} = 1.411 \text{ g Cl}$

<p>Part (c)</p> <ul style="list-style-type: none"> The most common error here was using the wrong molar mass of chlorine. Most frequently, 12.01 g/mol was used. Some students did not show work and had only an answer; no points were awarded unless work was shown. 	<p>Part (c)</p> <ul style="list-style-type: none"> $1.411 \text{ g Cl} \cdot 1 \text{ mol}/35.45 \text{ g} = 0.0398 \text{ mol Cl}$ (incorrect answer carried forward from b) $2.504 \text{ g} \cdot 1 \text{ mol}/35.45 \text{ g} = 0.07063 \text{ mol Cl}$
<p>Part (d)</p> <ul style="list-style-type: none"> Using non-whole numbers for subscripts in the empirical formula. Students did not divide by the fewest moles to get the simplest whole-number ratios. Calculating ratios by dividing by the largest number of moles rather than the smallest number of moles. Some students did not show work and had only an answer; no points were awarded unless some form of work consistent with an answer of MnCl_2 [or answer consistent with part (c)] was shown. 	<p>Part (d)</p> <ul style="list-style-type: none"> $0.0199 \text{ mol Mn}/0.0199 = 1 \text{ mol Mn}$ $0.0398 \text{ mol Cl}/0.0199 = 2 \text{ mol Cl} \Rightarrow \text{MnCl}_2$ The point was earned if work was shown and an incorrect answer was carried forward from (c): $0.07063 \text{ mol Cl}/0.0199 \text{ mol} = 3.5 \text{ mol Cl}$ $0.0199 \text{ mol Mn}/0.0199 \text{ mol} = 1 \text{ mol Mn}$ multiply by 2 to get whole numbers $\Rightarrow \text{Mn}_2\text{Cl}_7$
<p>Part (e)</p> <ul style="list-style-type: none"> Stating the moles of Cl would stay the same because the ratio of Mn and Cl wouldn't change or the concentration (M) of the solution isn't changing. Vague responses that did not refer to the experimental data or connect the lower Cl moles to the lower Mn_xCl_y quantity (e.g., "moles of Cl would be lower because some splattered out"). 	<p>Part (e)</p> <ul style="list-style-type: none"> The number of moles of Cl would be less than the number of moles calculated in part (c) because the final mass of the beaker and Mn_xCl_y would be lower.

<p>Part (f)(i)</p> <ul style="list-style-type: none"> The most common error in this question was adding all three half-reactions together. In some cases, students added all three half-reactions together and then multiplied one of them by 2 so the electrons would cancel out. In some cases, species on both sides were not removed. 	<p>Part (f)(i)</p> <ul style="list-style-type: none"> $\text{Zn} + 2 \text{MnO}_2 \rightarrow \text{Mn}_2\text{O}_3 + \text{ZnO}$ (This response earned the point with no work because the student could have done the work internally using the table provided to them right above the question; it was also not required to include states of matter to earn the point.) Responses where the two half-reactions were clearly written with the electrons, OH^-, and H_2O crossed out and the net ionic equation shown.
<p>Part (f)(ii)</p> <ul style="list-style-type: none"> A common error was an answer that was inconsistent with the net ionic reaction reported in part (f)(i). A second error was adding half-reactions 2 and 3 together, along with simply adding the corresponding reduction potentials. 	<p>Part (f)(ii)</p> <ul style="list-style-type: none"> $0.15 + 1.28 = 1.43 \text{ V}$ If part (f)(i) has a net ionic equation and shows work consistent with adding half-reactions 2 and 3 together without reversing reaction 2, then the E°_{cell} calculation: $(-1.28 + 0.15) = -1.13 \text{ V}$ *This is an example of the consistency policy which was applied to any incorrect part (f)(i).
<p>Part (f)(iii)</p> <ul style="list-style-type: none"> A common error used a value for n (moles of electrons) that was not 2 or used a value for n inconsistent with equation in part (f)(i). Incorrect conversions from J to kJ. Examples: <ul style="list-style-type: none"> $\Delta G^\circ_{\text{rxn}} = -(2)(96,485)(1.43) = -275,947 \text{ kJ}$ $\Delta G^\circ_{\text{rxn}} = -(2)(96,485)(1.43)(1000) = -2.76 \times 10^6 \text{ kJ}$ 	<p>Part (f)(iii)</p> <ul style="list-style-type: none"> $\Delta G^\circ_{\text{rxn}} = -(2)(96,485)(1.43)/1000 = -276 \text{ kJ/mol}_{\text{rxn}}$ $\Delta G^\circ_{\text{rxn}} = -(2)(96,485)(1.43) = -275,947 \text{ J/mol}_{\text{rxn}}$

<p>Part (f)(iv)</p> <ul style="list-style-type: none"> • Responses offered vague answers that omits key words that are important. Examples: <ul style="list-style-type: none"> ○ “I disagree because the anode loses mass and the cathode gains mass.” This response does not adequately convey an understanding and application of the conservation of mass. ○ “I disagree because mass can never be created or destroyed.” This response gives only a definition of conservation of mass and does not demonstrate understanding of the operation of the cell. • Responses that focused only on electrons and, since electrons have basically no mass, the mass of the battery is constant; not recognizing the chemical reactions taking place. • Responses that agreed with the claim because mass is lost from the anode were common, illustrating a misconception about the conservation of mass. 	<p>Part (f)(iv)</p> <ul style="list-style-type: none"> • “I disagree with the student because although the anode loses mass, that mass is transferred to the cathode within the battery, so the mass does not decrease in accordance with the law of conservation of mass.” • “I disagree because the anode loses mass, and the cathode gains that same mass, so no mass is lost.” • “I disagree with the student because the anode is actually gaining mass as Zn is oxidized to ZnO.” • “No, the total mass remains constant because if one part of the battery loses mass, then another part gains mass as no gases or liquids are formed in the net ionic equation.” • “I disagree because the battery is a closed system so no mass can enter or leave.” • “I disagree because all chemical components are solids so nothing can escape.”
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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. Distinguish between an electron configuration and an orbital diagram. We did give the point if a student drew an orbital diagram with all subshells correctly labeled and in the right order, with the electrons correctly shown in those subshells, but it is important to distinguish the two.
2. Work more often with experimental data and showing students how to use them. In this question, students could arrive at the right answer using stoichiometry, making the assumption that the chemical formula of Mn_xCl_y was $MnCl_2$ (a common compound). However, that was not the intent of the question because they were told that the subscripts ‘x’ and ‘y’ were unknown.
3. Make sure students know they must show work for calculations—we saw many correct answers that we could not give credit for because they lacked a supporting setup.
4. Empirical formula calculations—emphasize that students can arrive at a whole-number formula most easily if they divide by the fewest number of moles, rather than the largest number, to obtain the ratio that corresponds to the empirical formula. On occasion, students correctly calculated the 2:1 ratio and then put the subscript of 2 on the Mn. Also, emphasize that subscripts must be whole numbers, as some responses reported the decimal values of mass or moles as the subscripts.
5. When asked to explain or provide a justification for the effects of an error, such as in parts (e) and (f)(iv), be specific with language and the identity of substances (e.g., state “ Mn_xCl_y ” rather than “solution,” “something,” or “it”).

6. Electrochemical cells only use two half-reactions to make a whole reaction. Emphasize that students cannot multiply half-reaction cell potentials like they can thermodynamic quantities; electric potential is an intensive property unlike enthalpy and free energy, which are extensive. Unit analysis can be helpful (E is in volts, not volts/mol, whereas enthalpy and free energy are in $\text{kJ/mol}_{\text{rxn}}$). Encourage students to do unit analysis, remember to convert between J and kJ, and pay attention to signs.

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 1.1, 1.3, 1.5, 1.7, 9.7, and 9.8.
- Teachers can use AP Classroom to direct students to the AP Exam On-Demand Reviews: [2023 Session 6: FRQ \(Long\)](#), [2023 Session 7: FRQ \(Long\)](#), [2021 Session 6: Experimental Methods & Analysis of Free-Response Questions](#), [2021 Session 7: Everything You Need to Know about Electrochemistry](#), and [2021 Session 8: Free-Response Medley & Exam Strategies](#).
- Teachers can assign topic questions and/or progress checks in AP Classroom to monitor student progress and identify areas that need additional instruction or content and skill development. Teachers can also create custom quizzes from previously administered AP exam items from the Question Bank to help students practice and refine their understanding of key topics.

Question 2

Task: AlCl_3 structure and reactions

Topic: Stoichiometry, Hess's law, bonding and potential energy, VSEPR theory, formal charge, and equilibrium constants.

Max Score: 10

Mean Score: 5.22

What were the responses to this question expected to demonstrate?

Question 2 presented students with a series of chemical reactions involving aluminum, chlorine, and the compound AlCl_3 .

Part (a) of this question required students to apply the concepts of stoichiometry (Learning Objective SPQ-4.A, Skill 5.F from the *AP Chemistry Course and Exam Description*) to calculate the mass in grams of $\text{Cl}(g)$ from a balanced equation that represents the decomposition of gaseous AlCl_3 into gaseous Al and gaseous Cl.

Part (b) asked students to apply the concepts of Hess's law (ENE-3.C, 5.F) to calculate the value of $\Delta H^\circ_{\text{rxn}}$ for the decomposition reaction in part (a). Given a table of standard enthalpy values for three formation reactions, the first of two points was earned by either properly reversing the sign of ΔH_2 or multiplying the value of ΔH_4 by the factor of 3/2. The students earned the second point by correctly calculating the value of ΔH_1 for the overall reaction by manipulating both ΔH_2 and ΔH_4 correctly and adding them to ΔH_3 .

Part (c)(i) required students to properly interpret a potential energy diagram to determine the bond length for molecular chlorine, Cl_2 (SAP-3.B, 5.D).

Part (c)(ii) provided the bond length and bond energy for the Al–Cl bond and asked the students to draw the potential energy diagram for the Al–Cl bond, indicating the correct bond length (1st point) and the correct bond energy (2nd point) (SAP-3.B, 3.A).

Part (d)(i) provided three Lewis diagrams of AlCl_3 and asked students to identify the one structure that is not representative of trigonal planar geometry using the principles of VSEPR theory (SAP-4.C, 6.E).

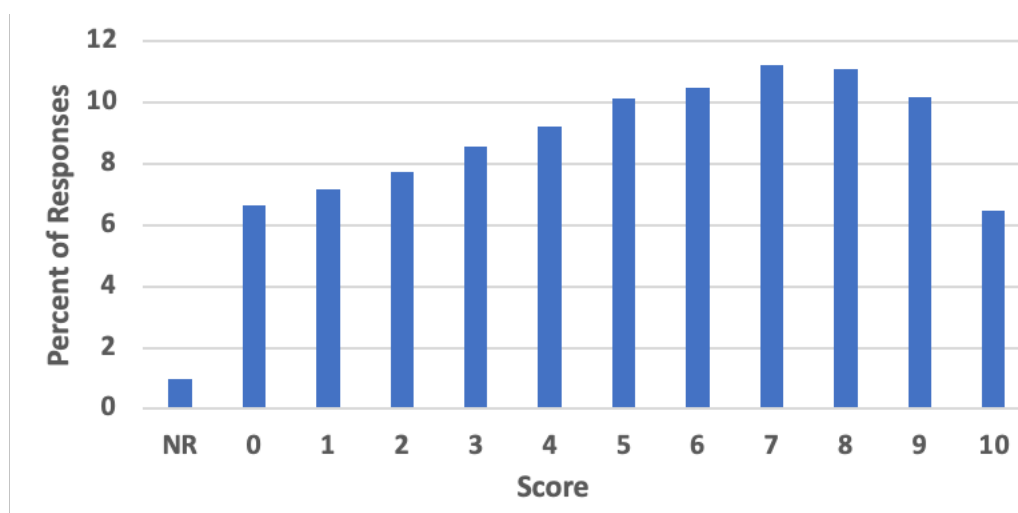
Part (d)(ii) asked students to identify which of the three provided Lewis diagrams was the best representation of AlCl_3 and justify that choice based on formal charges (SAP-4.B, 6.E).

Part (e) provided students with the dimerization reaction of AlCl_3 and required students to write the expression for the equilibrium constant, K_p , for the reaction (TRA-7.B, 5.B).

Part (f) prompted students to calculate the value of K_p using the equilibrium expression from part (e), the total pressure of the system, and a particle-level diagram that depicts the equilibrium mixture of AlCl_3 and Al_2Cl_6 (TRA-7.B, 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 2 was 5.22 out of a possible 10 points, with a standard deviation of 2.99 points. The distribution of scores on this question is shown below.



Part (a) was an accessible point for a slight majority of students. Student responses successfully integrated the skills required, using dimensional analysis, to obtain the correct value; however, many students had difficulty reporting their answer to the correct number of significant figures.

Students performed moderately well on part (b). Many students earned both points, with a smaller number earning the first point. Students were able to correctly manipulate the data provided and properly apply it to Hess's law to calculate the correct value for ΔH_1 .

The point in part (c)(i) was the most commonly earned point. Students were able to properly read the graph and determine that the internuclear distance was 200 picometers.

Students performed moderately well on part (c)(ii). Many students were capable of drawing a new potential energy diagram that was representative of minimum energy value (y-value) of -425 kJ/mol with an internuclear distance (x-value) of 220 picometers.

Students performed moderately well on part (d)(i). Students were generally able to recognize that diagram 2 was not a valid representation of AlCl_3 because the extra nonbonding (lone) pair of electrons would change the geometry from trigonal planar to trigonal pyramidal.

Part (d)(ii) was one of the two more challenging parts of the question for students. Students struggled with articulating that diagram 1 was the best representation for the bonding in AlCl_3 using a formal charge argument. Students had difficulty calculating the formal charges correctly for each individual atom, often resulting in choosing the wrong answer.

Students were moderately successful in earning the point in part (e). Generally, students were able to write the correct equilibrium expression for K_p based upon the chemical equation provided.

Part (f) was the second most challenging prompt on this question for students. Students struggled to correctly calculate the partial pressures of the two aluminum compounds, resulting in the wrong value for K_p being determined. Those students that were successful in earning the point in part (f) first calculated the pressures of the two compounds correctly.

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

<i>Common Misconceptions/Knowledge Gaps</i>	<i>Responses that Demonstrate Understanding</i>
<p>Part (a)</p> <ul style="list-style-type: none"> 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 (133 g Cl). Another common error was not converting the moles of Cl into grams of Cl. 	<p>Part (a)</p> <ul style="list-style-type: none"> Starting the calculation with the provided moles of aluminum chloride (1.25 moles), students were able to correctly convert to moles of chlorine (multiplying the moles of AlCl_3 by the molar ratio of (3 mol Cl:1 AlCl_3), then convert from moles of Cl to grams of Cl (multiplying by the molecular mass of $\text{Cl}(g)$).
<p>Part (b)</p> <ul style="list-style-type: none"> Adding together the three ΔH values provided in the table with no manipulation and reporting an overall ΔH_1 of -14 kJ/mol. Properly manipulating only one ΔH value (ΔH_2 or ΔH_4) in the table (does not earn second point). Only changing the sign of ΔH_2 as the value for the overall reaction ($\Delta H_1 = 1152 \text{ kJ/mol}$). Determining an overall ΔH_1 for a chemical equation in which the stoichiometric coefficients were not represented in the simplest whole number ratio ($2 \text{ AlCl}_3(g) \rightarrow 2 \text{ Al}(g) + 6 \text{ Cl}(g)$). 	<p>Part (b)</p> <ul style="list-style-type: none"> To earn the first point: correctly manipulate ΔH_2 by reversing the sign and/or multiplying ΔH_4 by the factor of $3/2$. To earn the second point: correctly calculate the ΔH_1 by applying Hess's law.
<p>Part (c)(i)</p> <ul style="list-style-type: none"> The most common error was misreading the curve and determining an internuclear distance outside the range of $200 \pm 10 \text{ pm}$. 	<p>Part (c)(i)</p> <p>The point was earned by correctly reading the graph and determining that the internuclear distance was 200 pm.</p>

<p>Part (c)(ii)</p> <ul style="list-style-type: none"> • The first point: The most common error was representing the minimum well or maximum peak with an x-value other than 220 ± 10 pm. • The second point: The most common error was representing the minimum of the energy well at a y-value other than -425 ± 20 kJ/mol. 	<p>Part (c)(ii)</p> <ul style="list-style-type: none"> • The first point was commonly earned by representing a minimum well or a maximum peak with an x-value of 220 ± 10 pm. • The second point was commonly earned by representing a well with a minimum y-value of -425 ± 20 kJ/mol.
<p>Part (d)(i)</p> <ul style="list-style-type: none"> • Eliminating diagram 1 because of an incomplete octet on Al (while true, not answering the prompt using VSEPR). • Eliminating diagram 2 because of an incorrect total number of electrons (while true, not answering the prompt using VSEPR). • Eliminating diagram 2 based upon a hybridization argument. • Eliminating diagram 3 because it has a double bond. • Using a VSEPR argument but providing an incorrect geometry (instead of stating trigonal pyramidal). • Simply stating that the Al having a lone pair was “the” problem. 	<p>Part (d)(i)</p> <p>After selecting diagram 2:</p> <ul style="list-style-type: none"> • shape/geometry would be trigonal pyramidal, not trigonal planar. • four electron domains are not trigonal planar. • the lone pair changes the bond angle specifically from 120° to $\sim 109^\circ$.

<p>Part (d)(ii)</p> <ul style="list-style-type: none"> Stating that the formal charge is zero for the compound and not the individual atoms. Stating that the formal charge was the charge of the ion (+3 for Al, and -1 for Cl). Stating that the valence electron count was the formal charge (3 for Al, and 7 for Cl). Choosing diagram 3 because aluminum has a complete octet with only three electron domains. 	<p>Part (d)(ii)</p> <p>After selecting diagram 1:</p> <ul style="list-style-type: none"> Correctly identifying the formal charges on Al and all three Cl atoms. Correctly identifying the formal charge on Al in diagram 1 and comparing it to the formal charge on Al in diagram 3. Correctly identifying the formal charge on Al in diagram 1 and comparing to the formal charge of Al in both diagram 3 and diagram 2, even if diagram 2 was eliminated in part (d)(i). If diagram 1 was eliminated in part (d)(i) then the point could be earned if the formal charges of all three atoms in diagram 3 were compared to the formal charges of all three atoms in diagram 2.
<p>Part (e)</p> <ul style="list-style-type: none"> $K_p = (P_{\text{Al}_2\text{Cl}_6}) / (P_{\text{AlCl}_3})^2$ $K_p = [P_{\text{Al}_2\text{Cl}_6}] / [P_{\text{AlCl}_3}]^2$ Responses that did not square the denominator 	<p>Part (e)</p> <ul style="list-style-type: none"> $K_p = (P_{\text{Al}_2\text{Cl}_6}) / (P_{\text{AlCl}_3})^2$ $K_p = P_{\text{Al}_2\text{Cl}_6} / P_{\text{AlCl}_3}^2$ $K_p = P_{\text{Al}_2\text{Cl}_6} / P_{\text{AlCl}_3}^2$
<p>Part (f)</p> <ul style="list-style-type: none"> The most common error was incorrectly calculating the partial pressures resulting with an incorrect value for K_p. Other common errors were students forgetting to square the denominator even with the correct expression in (e) and/or inverting the numerator and denominator. 	<p>Part (f)</p> <ul style="list-style-type: none"> Successful responses calculated the partial pressures of each gas correctly and then used them to calculate the value of K_p. <ul style="list-style-type: none"> $K_p = (6.63) / (15.47)^2 = 0.0277$ Responses that are consistent with an incorrect expression from part (e): <ul style="list-style-type: none"> $K_p = P_{\text{Al}_2\text{Cl}_6} / P_{\text{AlCl}_3} = 6.63 / 15.47 = 0.429$ $K_p = (P_{\text{Al}_2\text{Cl}_6})^2 / P_{\text{AlCl}_3} = (15.47)^2 / 6.63 = 36.1$ $K_p = P_{\text{AlCl}_3} / P_{\text{Al}_2\text{Cl}_6} = 15.47 / 6.63 = 2.33$

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. Make sure to emphasize the importance of reporting calculated values to the correct number significant figures.
2. Focus on how the ΔH value changes when an equation is either reversed or multiplied by a coefficient.
3. Highlight what a potential energy curve representing the formation of a bond looks like for your students. Make sure to emphasize that the optimal bond distance is always in a potential energy well.
4. Distinguish the difference between the basic electron arrangement (bonding pairs and lone pairs counted equally) versus the molecular geometry (bonding pairs and lone pairs counted uniquely). Focus on the calculation of formal charges and how they can be used to predict which Lewis diagram best represents the bonding arrangement in a molecule.
5. Emphasize the differences between a K_p and K_c expression.
6. Focus on the application of Dalton's law of partial pressures. Particularly for this type of question, emphasize how to relate the relative number of gas particles (mole fraction) to the partial pressure of an individual gas when supplied with the total pressure.

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 2.2, 2.6, 2.7, 4.5, 6.9, and 7.4.
- Teachers can use AP Classroom to direct students to the AP Exam On-Demand Reviews: [2022 Session 1: Graphical Analysis Review](#), [2022 Session 6: Thermodynamics Multiple-Choice and Free-Response Questions](#), and [2022 Session 8: Free-Response Question Medley](#).
- Teachers can use the [Atomic Interactions Simulation](#) from PhET to allow students to explore the nature of covalent bonding by interacting with the features of potential energy diagrams.
- Teachers can assign topic questions and/or progress checks in AP Classroom to monitor student progress and identify areas that need additional instruction or content and skill development. Teachers can also create custom quizzes from previously administered exam AP items from the Question Bank to help students practice and refine their understanding of key topics.

Question 3

Task: CaCO_3 reaction with HCl

Topic: Net ionic equation, Surface area and particle collisions, Kinetics, Stoichiometry, and Thermochemistry

Max Score: 10

Mean Score: 4.51

What were the responses to this question expected to demonstrate?

Question 3 presented students with a series of questions concerning an experiment in which solid calcium carbonate is reacted with an excess of aqueous hydrochloric acid.

Part (a) of this question required students to write the net ionic equation for the reaction between aqueous hydrochloric acid and solid calcium carbonate (Learning Objective TRA-1.B, Skill 5.E from the *AP Chemistry Course and Exam Description*).

Part (b) presented students with a table that lists time-of-reaction data for multiple trials of the reaction between HCl and CaCO_3 . Each trial either varies the HCl concentrations or the CaCO_3 particle size. The question asked students to explain the relationship between the rate of a chemical reaction and the experimental conditions (TRA-3.A, 2.E). The response was expected to confirm a claim, with an explanation using the experimental data, that one trial of a multitrial experiment is inconsistent with the other trials. The explanation can be based on the varying HCl concentrations or the CaCO_3 particle sizes.

Part (c) required students to make the connection between the number of particle collisions and the reaction times for two trials under different particle size reaction conditions. A student could earn up to 2 points in part (c). The first point was earned for correctly relating the particle size of a solid reactant to the surface area available for reaction (TRA-4.B, 6.F). The second point was earned for correctly relating the number of reactant particle collisions to the reaction times in the data table (TRA-4.B, 4.B).

The intent of part (d) was to analyze the data in the reaction timetable to determine the reaction order of the aqueous HCl reactant (TRA-3.B, 6.D). The student must determine that the claim of zero order is incorrect and cite data from the table as evidence.

Part (e) was a 2-point stoichiometry problem (SPQ-4.A, 5.F) involving the molarity of aqueous reactant remaining at the conclusion of a reaction (SPQ-3.A, 5.F). The first point was earned by correctly calculating the moles of HCl that will be consumed by the CaCO_3 . The second point was earned by subtracting those moles from the initial moles of HCl, then dividing that by the total solution volume to determine the molarity of HCl remaining.

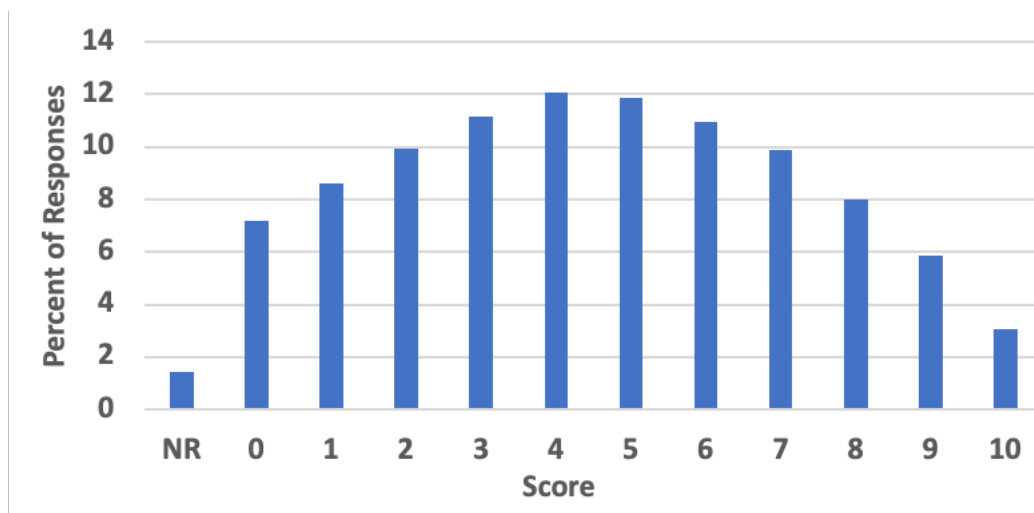
Part (f) provided temperature and time data for a calorimetry experiment using the CaCO_3 and HCl reaction. The student must state whether the reaction is exothermic or endothermic (ENE-2.A, 6.D), justifying their answer with information from the table.

Part (g) is a 2-point problem that asked the student to calculate the change in enthalpy of the reaction based on the experimental data presented in part (f) and other provided data. The first point was earned by successfully calculating the heat (q) absorbed by the solution (ENE-2.D, 5.F). The second point was earned by

dividing q by the moles of CaCO_3 reacted and applying the algebraic sign that is consistent with the response in part (f) (ENE-2.F, 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 3 was 4.51 out of a possible 10 points, with a standard deviation of 2.77 points. The distribution of scores on this question is shown below.



Part (a) was challenging for students. Successful responses recognized that the solid calcium carbonate reactant should be written as undissociated and that one of the products is the $\text{Ca}^{2+}(aq)$ ion, not a calcium atom. Most students did recognize that the chloride in aqueous HCl is a spectator ion, and they correctly represented the hydrochloric acid reactant as $\text{H}^+(aq)$ or $\text{H}_3\text{O}^+(aq)$. A large majority of the students were successful in balancing whatever equation that they came up with.

Part (b) was accessible for most students. Students who successfully responded to part (b) were able to use the given data table to recognize trends in reaction times upon varying reaction conditions. These students were then able to justify why trial 5 was an outlier within those trends.

A majority of students were able to earn at least one of the two points in part (c). A portion of those students successfully related smaller particle size to greater surface area for the reaction to occur. Others were able to communicate that an increase in the number of particle collisions would decrease the time needed to complete the reaction. Many students were able to earn both points by communicating both of these concepts.

Part (d) was successfully answered by a majority of students. Regardless of how well they communicated their actual analysis of the data, these students were able to convey that the reaction can't be zero order with respect to HCl if a change in HCl concentration causes a change in reaction time.

Students were moderately successful in earning the first point in part (e). Students were able to utilize the stoichiometric ratio from the given molecular equation to calculate the moles of HCl consumed based on the moles of CaCO_3 reacted. The second point in part (e) was very challenging for students. The minority of students who earned this point were able to recognize that the question was asking for the concentration of HCl that remains after the completion of the reaction, and not just the concentration that reacted. These students subtracted the moles (or molarity) of HCl consumed from the initial moles (or molarity) of HCl .

In part (f) a large majority of students were able to correctly determine that the reaction is exothermic, even if the students didn't end up earning the point. The students who were successful on part (f) were the ones who used specific data from the table to justify their answer, as required by in the stem of the question.

Part (g)(i) was the most accessible point on Question 3. A large majority of students were able to correctly calculate the heat (q) absorbed by the solution given the data in the table, the provided specific heat capacity of the solution, and the provided mass of the solution.

Part (g)(ii) was far more challenging for students because three different conversions needed to be performed successfully to earn the point for this part. The students who earned the point were able to convert the mass of CaCO_3 reactant to moles, convert the q from joules to kilojoules, and divide the q (in kJ) by the moles of CaCO_3 to calculate the ΔH of the reaction.

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

Common Misconceptions/Knowledge Gaps	Responses that Demonstrate Understanding
<p>Part (a)</p> <ul style="list-style-type: none"> • Writing the solid CaCO_3 as dissociated in the net ionic equation. • Not treating Cl^- as a spectator ion. 	<p>Part (a)</p> <ul style="list-style-type: none"> • $\text{CaCO}_3(s) + 2 \text{H}^+(aq) \rightarrow \text{Ca}^{2+}(aq) + \text{H}_2\text{O}(l) + \text{CO}_2(g)$ • $\text{CaCO}_3(s) + 2 \text{H}_3\text{O}^+(aq) \rightarrow \text{Ca}^{2+}(aq) + 3 \text{H}_2\text{O}(l) + \text{CO}_2(g)$
<p>Part (b)</p> <ul style="list-style-type: none"> • Stating that trial 5 should have had a shorter reaction time than trial 6 without providing a justification based on trials 1–3. 	<p>Part (b)</p> <p>There are two common response pathways that students used to earn the point:</p> <ul style="list-style-type: none"> • For trials 1–3, the reaction time increases as particle size increases, so the reaction time for small particle sizes should be between the time for fine powder and large chunks. But trial 5 with small chunks has a reaction time that is greater than trial 6 with large chunks, which is inconsistent with the rest of the data. • Trials 1 and 4 have the same particle sizes, but trial 4 uses 3.0 M HCl instead of 1.0 M HCl, causing trial 4 to have a shorter reaction time. But trial 5 is inconsistent because it should have a shorter reaction time than trial 2 since they are both the same particle size, but its time is much longer than that of trial 2.

<p>Part (c)</p> <ul style="list-style-type: none"> • Many students referenced surface area but not collisions, and vice versa. • A common mistake was only stating that smaller particles have a larger surface area for reactions to occur on, without explicitly stating that the number of collisions themselves will be greater. 	<p>Part (c)</p> <ul style="list-style-type: none"> • The reaction time for trial 2 is less than that for trial 3 because the smaller chunks in trial 2 have a greater surface area than the larger chunks in trial 3. With greater surface area, there will be a greater number of collisions which results in a shorter reaction time.
<p>Part (d)</p> <ul style="list-style-type: none"> • The most common error in this part was trying to justify the response without any specific reference to data from the table. 	<p>Part (d)</p> <ul style="list-style-type: none"> • Disagree. In trial 1 (fine powder), the [HCl] was 1.0 M and the reaction time was 67 seconds. In trial 4 (also fine powder), the [HCl] was 3.0 M and the reaction time was 22 seconds. If the reaction was zero order, the reaction time would not change when the concentration of HCl changes.
<p>Part (e)</p> <ul style="list-style-type: none"> • The most common error in this part was calculating the molarity of HCl that was consumed. • The second most common error was assuming that the moles of HCl reacted would be equal to the moles of CaCO₃ reacted. 	<p>Part (e)</p> <ul style="list-style-type: none"> • $0.0500 \text{ L} \times 1.00 \text{ M HCl} = 0.0500 \text{ mol HCl}$ • $1.00 \text{ g CaCO}_3 \times \frac{1 \text{ mol CaCO}_3}{100.09 \text{ g CaCO}_3} \times \frac{2 \text{ mole HCl}}{1 \text{ mol CaCO}_3} = 0.0200 \text{ mol HCl}$ • $0.0500 \text{ mol HCl} - 0.0200 \text{ mol HCl} = 0.0300 \text{ mol HCl remaining}$ • $0.0300 \text{ mol HCl} \div 0.0500 \text{ L} = 0.600 \text{ M HCl remaining}$
<p>Part (f)</p> <ul style="list-style-type: none"> • The most common error in this part was assuming that a temperature increase of the solution indicates an endothermic reaction. • Another common error was providing a “heat exchange” explanation for why the reaction is exothermic without ever referencing the data in the table, as required by the question. 	<p>Part (f)</p> <ul style="list-style-type: none"> • The reaction is exothermic because the temperature of the solution is increasing, which means that the reaction is releasing heat to the solution.

<p>Part (g)(i)</p> <ul style="list-style-type: none"> The most common error was treating the final temperature of the solution as ΔT. 	<p>Part (g)(i)</p> <ul style="list-style-type: none"> $q = (51.0 \text{ g})(4.0 \frac{\text{J}}{\text{g}\cdot\text{C}})(0.70^\circ\text{C}) = 140 \text{ J}$
<p>Part (g)(ii)</p> <ul style="list-style-type: none"> The most common error in this part is simply converting the answer from (g)(ii) from J to kJ. The second most common error is not applying the negative sign when the reaction was identified as “exothermic” in part (f). 	<p>Part (g)(ii)</p> <ul style="list-style-type: none"> $1.00 \text{ g CaCO}_3 \times \frac{1 \text{ mol CaCO}_3}{100.09 \text{ g CaCO}_3} = 0.0100 \text{ mol CaCO}_3$ $\Delta H = -0.140 \text{ kJ} \div 0.0100 \text{ mol CaCO}_3 = -14 \text{ kJ/mol}_{\text{rxn}}$

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 your students that when a question states that an explanation must be based on given data, they should cite specific details from the data in their explanation, not just a generic reference to the data.
2. Even though the isolated “net ionic equation question” of the FRQ portion of the exam was discontinued in 2013, equation writing is still a tested topic (see Topics 4.2 and 4.3 in the *AP Chemistry Course and Exam Description*). Emphasis should be placed on knowing which species should be written as dissociated into ions and which species should not.
3. Students need more practice determining the enthalpy of reaction using calorimetry data for reactions occurring in aqueous solution. Place special emphasis on determining the correct algebraic sign, as well as identifying the quantity of moles needed in the denominator of $q/\text{mol}_{\text{rxn}}$. Using the convention of moles of reaction (mol_{rxn}) is an effective strategy, particularly in reactions that have coefficients other than 1.
4. When a question asks whether the student agrees or disagrees with a claim, the student should clearly respond with “I agree” or “I disagree” somewhere in their response, preferably at the start.
5. A significant portion of the exam involves explaining or justifying chemical processes and observations. Give your students a lot of practice with these types of questions and provided detailed feedback on how better to communicate these explanations clearly using the correct vocabulary. Claim/Evidence/Reasoning (CER) charts can be helpful heuristics for students to organize their responses and ensure that they include all parts of a complete argument.

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 4.2, 4.5, 5.1, 5.2, 5.5, 6.1, 6.4, and 6.6.
- Teachers can use AP Classroom to direct students to the AP Exam On-Demand Reviews: [2023 Session 2: FRQ \(Short\)](#), [2022 Session 2: Kinetics Multiple-Choice and Free-Response Questions](#), and [2021 Session 3: Experiment-Based Free-Response: Calorimetry & Beer's Law](#).
- Teachers can show students animations of the effect of changing surface area on the frequency of particle collisions with the surface of a solid, such as [Surface area and chemical reactions animation](#) from the Science Photo Library.
- Teachers can use the article on AP Central on [Units in Thermochemical Calculations](#) to help students better understand how to work with the mol_{rxn} convention in thermochemical calculations.
- Teachers can direct students to the "[Write This, Not That](#)" document in the Resources section 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 need additional instruction or content and skill development. Teachers can also create custom quizzes from previously administered AP exam items from the Question Bank to help students practice and refine their understanding of key topics.

Question 4

Task: $\text{CH}_3\text{NH}_2/\text{CH}_3\text{NH}_3^+$ buffer

Topic: Molar mass, solution preparation, lab techniques, and buffers

Max Score: 4

Mean Score: 1.66

What were the responses to this question expected to demonstrate?

Question 4 presented students with an array of questions concerning the preparation and analysis of buffer solutions with equimolar amounts of the weak base, CH_3NH_2 , and its conjugate acid, CH_3NH_3^+ .

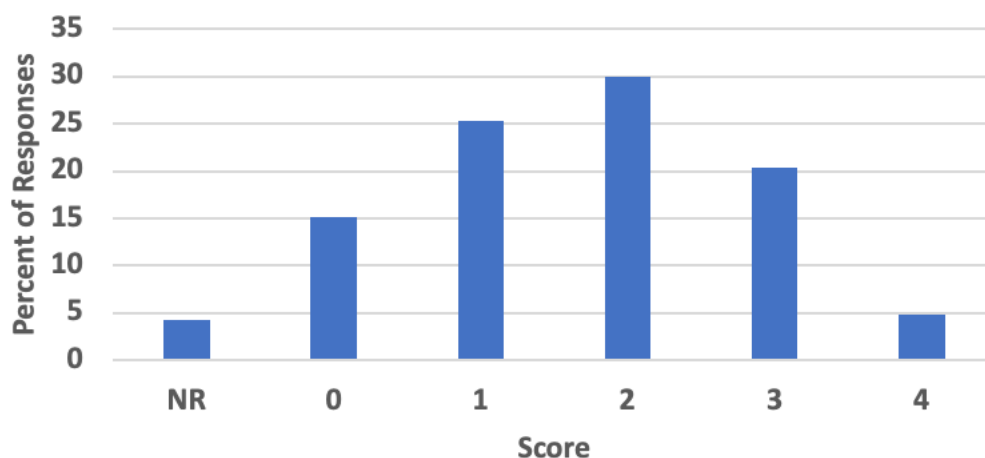
Part (a) required students to apply mathematical routines to determine the mass of $\text{CH}_3\text{NH}_3\text{Cl}(s)$ required to prepare the desired buffer (Learning Objective SPQ-1.A, Skill 5.F from the *AP Chemistry Course and Exam Description*). The student must use the periodic table to determine the molar mass of $\text{CH}_3\text{NH}_3\text{Cl}$ to convert a given mole value to grams to earn the point.

Part (b) required students to identify appropriate experimental procedures required to accurately weigh a mass of solid (SPQ-1.A, 2.C) and prepare a buret to deliver a precise volume of solution (SPQ-3.A, 2.C). The students were presented with an incomplete procedure and tasked with filling in two missing procedural steps. The first point was earned for the correct selection of the electronic balance to measure the mass of $\text{CH}_3\text{NH}_3\text{Cl}(s)$ calculated in part (a) in Step 1 of the procedure. The second point was earned for rinsing the wet buret with the 0.100 M CH_3NH_2 solution prior to filling it with the 0.100 M CH_3NH_2 , in order to prevent dilution of the solution in Step 4 of the procedure.

Part (c) required students to integrate mathematical and conceptual reasoning to predict the outcome of an experimental modification to the preparation of the buffer (SAP-10.C, 2.F). The procedure was modified by halving both the moles of CH_3NH_2 and the mass of $\text{CH}_3\text{NH}_3\text{Cl}$. The point was earned for a response that indicates the pH would remain the same, employing a mathematical and/or conceptual justification that the mole ratio of buffer components is the same as in the first buffer solution; therefore, the pH of the second solution is the same as the first solution.

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 1.66 out of a possible 4 points, with a standard deviation of 1.15 points. The distribution of scores on this question is shown below.



Most responses attempted part (a), and it was an accessible point for students to earn. Many students who earned the point clearly showed the use of dimensional analysis to connect the given number of moles to the corresponding mass of the substance. The preponderance of responses included the correct units and reported the numerical value to the correct number of significant figures.

The first point of part (b) demonstrated that students understood that the electronic balance was required to measure the mass of a substance. Responses were less consistent in the use of weighing paper and/or the use of the small spatula to transfer the solid to the balance. The second point of part (b) suggests that students may not be familiar with the use of burets or the skill needed to prepare burets for proper use. Part (b) also indicated students are not skilled in writing replicable procedures. Many responses used vague language that may or not have been meant to direct one to rinse and refill the buret with an appropriate amount of 0.100 M CH_3NH_2 .

The responses in part (c) showed that students are familiar with the use of the Henderson-Hasselbalch equation ($\text{pH} = \text{p}K_a + ([\text{A}^-]/[\text{HA}])$) when calculating the pH of a buffer. The overwhelming majority of responses that approached part (c) mathematically used $\text{pH} = \text{p}K_a + \log([\text{CH}_3\text{NH}_2]/[\text{CH}_3\text{NH}_3^+])$ to calculate the pH value of the second buffer. There were a significant number of responses that indicated that students were not aware that the K_b value of CH_3NH_2 was given in the prompt instead of the K_a value of $\text{CH}_3\text{NH}_3\text{Cl}$. For responses that used a conceptual instead of a mathematical approach, the preponderance of responses recognized the importance of the ratio of the conjugate acid to the weak base when constructing their claim and justification.

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

<i>Common Misconceptions/Knowledge Gaps</i>	<i>Responses that Demonstrate Understanding</i>
<p>Part (a)</p> <ul style="list-style-type: none"> The most common error was using an incorrect molar mass of $\text{CH}_3\text{NH}_3\text{Cl}$. 	<p>Part (a)</p> <ul style="list-style-type: none"> Beginning the calculation with the moles of $\text{CH}_3\text{NH}_3\text{Cl}$ given in the prompt (0.00250 moles), students were able to correctly multiply the moles by the molar mass of $\text{CH}_3\text{NH}_3\text{Cl}$ (67.52 g/mol) to determine the mass (in grams) of $\text{CH}_3\text{NH}_3\text{Cl}$ needed to prepare the buffer.
<p>Part (b)</p> <ul style="list-style-type: none"> Students did not explicitly identify that the electronic balance was needed to measure mass of a substance. Students did not recognize the need to rinse the wet buret with the 0.100 M CH_3NH_2 to prevent dilution of the solution. Students did not recognize the need to refill the buret with the 0.100 M CH_3NH_2 solution after rinsing it with the solution. 	<p>Part (b)</p> <ul style="list-style-type: none"> Common correct response for the first point: Place weighing paper on the electronic balance and use the small spatula to measure 0.169 g $\text{CH}_3\text{NH}_3\text{Cl}$. Common correct response for the second point: Rinse the buret with a small amount of the 0.100 M CH_3NH_2. Drain the remaining solution through the tip of the buret and refill with 0.100 M CH_3NH_2.
<p>Part (c)</p> <ul style="list-style-type: none"> Students using mathematical reasoning substituted the K_b of CH_3NH_2 into the Henderson-Hasselbalch equation, yielding the pOH value instead of the pH value. Students who failed to subtract the pOH from 14 would incorrectly state that the pH decreased. 	<p>Part (c)</p> <ul style="list-style-type: none"> The pH of a buffer is determined by the pK_a and the ratio of the conjugate acid-base pair. $[\text{CH}_3\text{NH}_3\text{Cl}]$ and $[\text{CH}_3\text{NH}_2]$ were both reduced by half; therefore, their mole ratio is constant, and the pH of the second buffer is equal to the pH of the first buffer.

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 the importance of using dimensional analysis to demonstrate mathematical routines with clarity and correctness.
2. Offer students adequate exposure to laboratory experiences that require them to write replicable procedures.
3. Offer students adequate exposure to laboratory equipment and the proper techniques to use when utilizing the equipment.
4. When using formulas from the equation sheet, emphasize the relationships that the equations represent. Often, students do not need to conduct lengthy mathematical routines to justify relationships between variables.
5. Expose students to buffer systems that are comprised of weak acids and their conjugate bases as well as buffers that are comprised of weak bases and their conjugate acids.

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 1.1, 3.7, 8.4, and 8.9.
- Teachers can use AP Classroom to direct students to the AP Exam On-Demand Reviews: [2023 Session 6: FRQ \(Long\)](#) and [2021 Session 6: Experimental Methods & Analysis of Free-Response Questions](#).
- Teachers can have students complete the [Preparing Solutions Simulation](#) on the [American Association of Chemistry Teachers \(AACT\) website](#) as a prelab to preparing their own solutions as part of a laboratory procedure. This allows students to understand the sequence of steps and calculations before using laboratory equipment.
- Teachers can assign topic questions and/or progress checks in AP Classroom to monitor student progress and identify areas that need additional instruction or content and skill development. Teachers can also create custom quizzes from previously administered AP exam items from the Question Bank to help students practice and refine their understanding of key topics.

Question 5

Task: HCl gas and strength of acids

Topic: Ideal gas law, representations of solutions, molecular structure of acids

Max Score: 4

Mean Score: 2.54

What were the responses to this question expected to demonstrate?

Question 5 presented students with gas laws involving HCl gas, as well as representations of acid solutions.

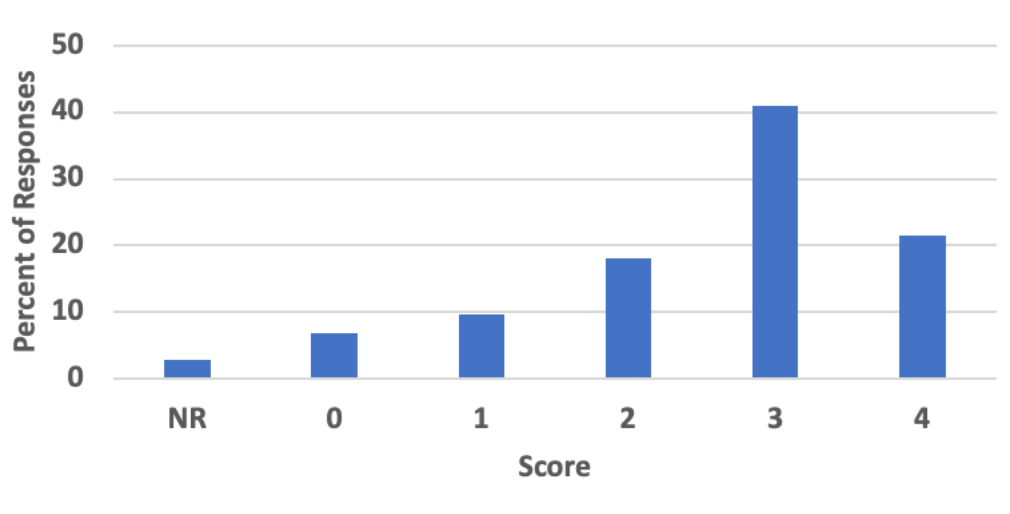
Part (a) involved using the ideal gas law for a sample of HCl(g). In part (a)(i) the number of moles of gas was calculated given the pressure, volume, and temperature. Part (a)(ii) utilized the calculated moles of gas from (a)(i) to calculate a new pressure at a lower given temperature (Learning Objective SAP-7.A, Skill 5.F from the *AP Chemistry Course and Exam Description*).

In part (b) the students were asked to draw three water molecules around a given chloride ion with correct ion-dipole orientation (SPQ-3.B, 3.C).

Part (c) asked the students to select which acid is represented by a particle diagram, given three to choose from. The justification for the choice of acid is based on a table of given K_a values (SAP-9.F, 6.C).

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 2.54 out of a possible 4 points, with a standard deviation of 1.21 points. The distribution of points on this question is shown below.



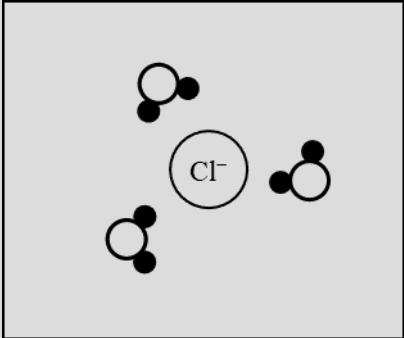
Parts (a)(i) and (a)(ii) were accessible points for the majority of students. Student responses successfully integrated the skills required, using the ideal gas law with correct dimensional analysis to obtain the correct value reported to the correct number of significant figures.

Students performed very well on part (b), correctly orienting three water molecules such that hydrogen atoms are oriented toward the chloride ion. Representing the interactions between the hydrogens (dark circles) in water molecules with the Cl⁻ ion was essential.

Most students did not earn credit for part (c), as the justification failed to show both the fact that HNO₂ was the only weak acid listed in the table and that the particle diagram represented a weak acid dissociation. The students are presented with a table of three acids (one weak and two strong), their conjugate bases, and their corresponding K_a values. A particle diagram was given with nine particles, seven of which represented un-ionized HA molecules, and the remaining two illustrated the representative ionization of a single HA molecule into an A⁻ ion and H₃O⁺ ion. Students were asked to choose which of the three acids corresponded to the particle diagram with justification from the table. In order to earn this point, students had to select HNO₂ since its K_a was less than 1. Students also had to state in some fashion that the diagram corresponded to the dissociation of a weak acid or partially ionized HA.

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

Common Misconceptions/Knowledge Gaps	Responses that Demonstrate Understanding
<p>Part (a)(i)</p> <ul style="list-style-type: none"> Using an invalid value for R (incorrect unit analysis) Algebraic mistake or equation rearrangement for calculating the inverse (e.g., $n = RT/PV$) 	<p>Part (a)(i)</p> <ul style="list-style-type: none"> $n = \frac{PV}{RT} = \frac{(7.45 \text{ atm})(6.00 \text{ L})}{(0.08206 \frac{\text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}})(296 \text{ K})} = 1.84 \text{ mol}$
<p>Part (a)(ii)</p> <ul style="list-style-type: none"> Using an incorrect mathematical equation, usually $P_1 T_1 = P_2 T_2$ Making errors in algebra or computation Using the volume in place of the pressure to solve for the new pressure Solving for moles of gas at the new temperature using the given initial pressure from (a)(i) 	<p>Part (a)(ii)</p> <p>Both the volume and number of molecules are constant, therefore</p> <ul style="list-style-type: none"> $P_2 = \frac{(P_1)(T_2)}{T_1} = \frac{(7.45 \text{ atm})(271 \text{ K})}{296 \text{ K}} = 6.82 \text{ atm}$ $P = \frac{nRT}{V} = \frac{(1.84 \text{ mol})(0.08206 \frac{\text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}})(271 \text{ K})}{6.00 \text{ L}} = 6.82 \text{ atm}$

<p>Part (b)</p> <ul style="list-style-type: none"> • Drawing a majority of water molecules with the oxygen atom (large unshaded circle) oriented toward the Cl^- ion. • Labelling the oxygen atom (unshaded circle) in water as H^+ and orienting it toward the Cl^- ion. 	<p>Part (b)</p> <ul style="list-style-type: none"> • A drawing that shows three water molecules with a hydrogen atom (shaded circle) oriented toward the Cl^- ion. 
<p>Part (c)</p> <ul style="list-style-type: none"> • Not describing the diagram as being for a partially dissociated acid. • Using the terms “dissolve” or “solubility” instead of “dissociate” or “ionize.” • Stating that HNO_2 had the “weakest” or “smallest” K_a without giving a value of less than 1. • Not eliminating HCl or HClO_4 as choices due to them being strong acids and fully dissociated, which did not agree with the diagram. 	<p>Part (c)</p> <ul style="list-style-type: none"> • HNO_2. The diagram shows most of the molecules in their un-ionized form, indicating a weak acid with a K_a value less than 1, which is consistent only with HNO_2.

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. Encourage students to use correct and complete dimensional analysis in all calculations to avoid simple mistakes, such as choosing the wrong value for given variables and constants or not calculating to the correct significant figures in the answer. Require students to use units in all of their intermediate calculations to avoid simple errors, such as using the incorrect version of the gas constant, R , or using $^{\circ}\text{C}$ instead of K .
2. When drawing particle diagrams, emphasize the importance of interpreting and communicating with relevant scale, such as hydrogen is a smaller atom than oxygen, so the smaller circle must represent hydrogen.
3. Review ion-dipole interactions with respect to the permanent dipole in water; this is an important intermolecular force in solutions.
4. Strengthen students' skills in writing clear answers that include relevant details. Responses like “ HNO_2 has the lowest/smallest K_a ” or “the weak acid doesn't dissolve very much” did not receive credit.

Encourage students to follow the Claim/Evidence/Reasoning (CER) model to provide complete explanations. Stating a correct answer choice by itself is an incomplete explanation. The student should look to the prompt in the question for important details to include their justification.

5. Emphasize that acid-base chemistry is a proton transfer process in which the ionic charges of species also change.

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 3.4, 3.8, 8.4, and 8.6.
- Teachers can use AP Classroom to direct students to the AP Exam On-Demand Reviews: [2021 Session 5: Understanding Acid-Base Equilibrium](#).
- Teachers can have students analyze or create particle diagrams to contrast between acid solutions that are strong/weak as well as concentrated/dilute and have them relate these to K_a values. The Royal Society of Chemistry [Educational Resource on Acid Strength](#) provides a series of diagrams, and the ChemEd Xchange blog gives a [lesson on the relationships between acid strength, \$K_a\$, pH, molarity, and percent ionization](#).
- Teachers can assign topic questions and/or progress checks in AP Classroom to monitor student progress and identify areas that need additional instruction or content and skill development. Teachers can also create custom quizzes from previously administered AP exam items from the Question Bank to help students practice and refine their understanding of key topics.

Question 6

Task: HF and HBr IMFs and bonds

Topic: Intermolecular forces, properties of liquids, enthalpy of reaction, bond length, and atomic structure

Max Score: 4

Mean Score: 1.95

What were the responses to this question expected to demonstrate?

Question 6 prompted students to respond to various prompts regarding the properties of HBr(*l*) and HF(*l*).

Part (a) asked students to list all types of intermolecular forces of attraction present in pure samples of each of the two liquids (Learning Objective SAP-5.A, Skill 1.B from the *AP Chemistry Course and Exam Description*).

In part (b) students had the opportunity to earn 2 points.

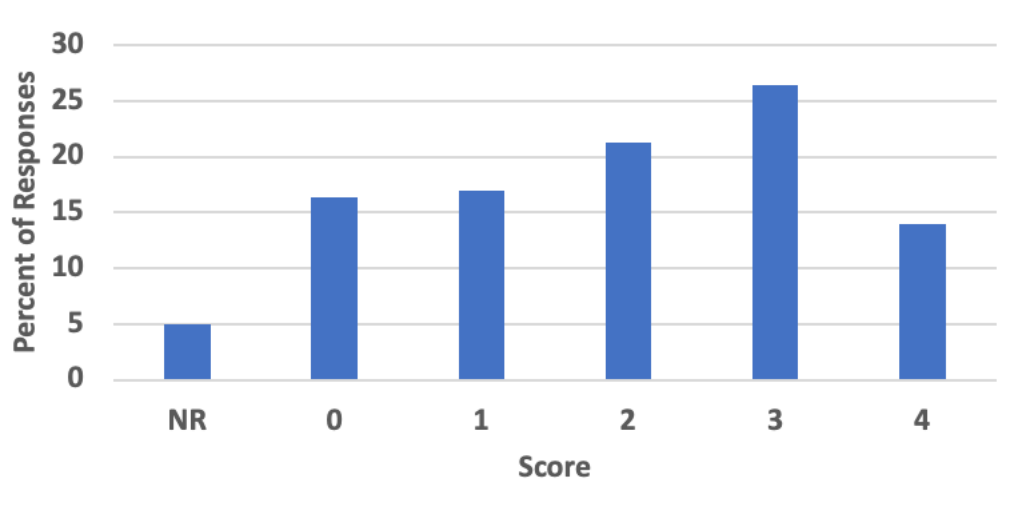
Part (b)(i) required students to explain why the molar enthalpy of vaporization of HF(*l*) is greater than that of HBr(*l*), based on the types and relative strengths of intermolecular forces of attraction present in each liquid. Successful responses provided an explanation that identified the strong hydrogen bonding present in HF(*l*), which is absent in HBr(*l*), as the reason for the difference (SAP-5.B, 4.C).

Part (b)(ii) asked students to determine the amount of heat required to vaporize a sample of liquid HF(*l*) given the mass of the sample; therefore, students were required to convert from the mass of HF(*l*) to moles, and then to kilojoules using the value of ΔH_{vap}° provided in the table (ENE-2.F, 5.F).

Part (c) required students to explain why the H–Br bond is longer than the H–F bond using principles of electron arrangements in the respective atoms. Successful responses indicated that the two additional occupied electron shells in Br versus F accounted for the difference in bond length (SAP-3.B, 4.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 6 was 1.95 out of a possible 4 points, with a standard deviation of 1.36 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 identified all the intermolecular forces of attraction in both $\text{HBr}(l)$ and $\text{HF}(l)$.

Students performed moderately well on part (b)(i). A slight majority were successful at connecting the greater value of $\Delta H_{\text{vap}}^{\circ}$ to stronger intermolecular forces of attraction in $\text{HF}(l)$, and that the additional intermolecular force of hydrogen bonding was responsible for the increased strength.

Part (b)(ii) was an accessible point for the majority of students. Student responses successfully used dimensional analysis to obtain the correct value for the energy required to vaporize 6.85 g of $\text{HF}(l)$.

Part (c) was a challenging prompt for students. Many students correctly recognized that the bromine atom was larger than the fluorine atom; however, they were unable to provide a valid explanation using the principles of atomic structure.

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

<i>Common Misconceptions/Knowledge Gaps</i>	<i>Responses that Demonstrate Understanding</i>
<p>Part (a)</p> <ul style="list-style-type: none">The most common error involved either the omission or inclusion of incorrect intermolecular forces of attraction for both $\text{HBr}(l)$ and/or $\text{HF}(l)$. Most common was the absence of dipole-dipole forces for $\text{HBr}(l)$.	<p>Part (a)</p> <ul style="list-style-type: none">Students were able to list London dispersion forces and dipole-dipole forces for both $\text{HBr}(l)$ and $\text{HF}(l)$ and hydrogen bonding for $\text{HF}(l)$.

<p>Part (b)(i)</p> <ul style="list-style-type: none"> • Many students were able connect the greater value of ΔH°_{vap} to stronger intermolecular forces of attraction but did not identify the force responsible. • A subset of students discussed intramolecular forces (covalent bonds) and electronegativity as the reason for the greater value. 	<p>Part (b)(i)</p> <ul style="list-style-type: none"> • Students were able to connect the greater value of ΔH°_{vap} to stronger intermolecular forces of attraction and to identify hydrogen bonding as the responsible force.
<p>Part (b)(ii)</p> <ul style="list-style-type: none"> • The most common error concerned failing to convert the mass of HF(<i>l</i>) to moles before multiplying by the ΔH°_{vap} to obtain an answer. • Some students incorrectly calculated the molar mass of HF(<i>l</i>). • Some students chose the wrong ΔH°_{vap} from the table. 	<p>Part (b)(ii)</p> <ul style="list-style-type: none"> • Starting the calculation with the provided mass of hydrogen fluoride (6.85 g), students were able to correctly convert to moles of hydrogen fluoride (dividing the mass by the molar mass), and then calculate the energy required using the correct ΔH°_{vap} from the table (multiplying the ΔH°_{vap} by the moles of hydrogen fluoride).
<p>Part (c)</p> <ul style="list-style-type: none"> • While many students were able to recognize that bromine had a larger radius than fluorine, they had a difficult time correlating the larger radius with the electron structure (two additional electron shells in a Br atom). • Periodicity, shielding arguments, and electron-electron repulsion without mentioning energy levels (shells) were common. 	<p>Part (c)</p> <ul style="list-style-type: none"> • Students were able to recognize that bromine had two more occupied electron energy levels than fluorine which resulted in a longer bond between the hydrogen and the halogen.

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. Encourage students to read each prompt thoroughly to guide them toward using the appropriate information when responding. On this question, many students did not answer part (b)(i) by discussing the types and relative strengths of the intermolecular forces in their response. Likewise, in part (c), a significant number of the students neglected to reference the arrangement of electrons as indicated by the prompt.
2. Address common misconceptions, such as covalent bonds breaking during phase changes, or that the strength of a covalent bond or electronegativity influences the enthalpy of vaporization, or that hydrogen bonds are always stronger than dipole-dipole and London dispersion forces.

3. Insist that students use correct terminology in their verbal answers. Responses that mentioned “London dispersion bonds” were given the benefit of the doubt, but those that only mentioned “bonds” or used the term “in HF” made it challenging to discern whether they were truly talking about intermolecular forces or referencing covalent bonds instead. Likewise, differentiate between energy levels (shells), orbitals (subshells), valence shells (subshells or orbitals), and electrons. Many students used the terms interchangeably. Provide students direct feedback in written work and require them to restate their answers if they are careless with their language, both when giving answer in writing or verbally.
4. Insist that students use full and complete setups for all calculations, including intermediate work and units. Students often failed to show sufficient work in the calculation of the moles of HF(*l*) in part (b)(ii).

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 2.2, 3.1, 3.2, and 6.6.
- Teachers can use AP Classroom to direct students to the AP Exam On-Demand Reviews: [2022 Session 6: Bonding and the Condensed State](#) and [2021 Session 4: Examining Coulomb’s Law, Periodicity, & Intermolecular Forces](#).
- Teachers can assign topic questions and/or progress checks in AP Classroom to monitor student progress and identify areas that need additional instruction or content and skill development. Teachers can also create custom quizzes from previously administered AP exam items from the Question Bank to help students practice and refine their understanding of key topics.

Question 7

Task: Strontium hydroxide K_{sp}

Topic: Particulate diagrams, solubility equilibrium concentrations, and experimental modifications

Max Score: 4

Mean Score: 2.23

What were the responses to this question expected to demonstrate?

Question 7 presented students with a set of questions surrounding the solubility equilibrium for strontium hydroxide.

Part (a) required students to interpret a particulate-level diagram that illustrates a dissociation of $\text{Sr}(\text{OH})_2$ into its ions. Students were expected to make a claim about how the ratio of Sr^{2+} and OH^- in the diagram is incorrectly illustrated (Learning Objective SPQ-3.B, Skill 6.A from the *AP Chemistry Course and Exam Description*).

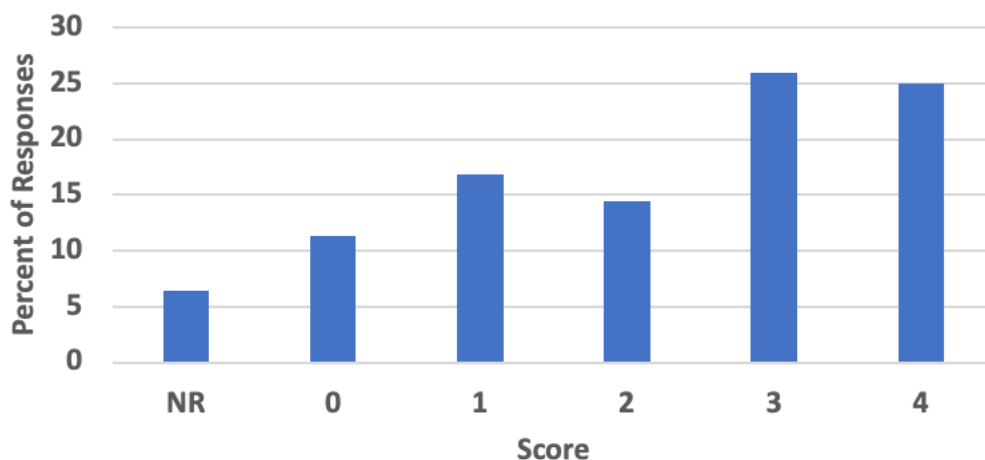
Part (b)(i) required students to calculate $[\text{OH}^-]$ using information given about $[\text{Sr}^{2+}]$ using the stoichiometric relationship. Identifying that the relationship between $[\text{OH}^-]$ and $[\text{Sr}^{2+}]$ is 2:1, students must calculate a value of $[\text{OH}^-]$ that is double that of $[\text{Sr}^{2+}]$ (SPQ-4.A, 5.F).

Using the information provided in part (b)(i) and the calculated value of $[\text{OH}^-]$, part (b)(ii) prompted students to calculate the K_{sp} value for the insoluble hydroxide using the provided K_{sp} expression (SPQ-5.A, 5.F).

In part (c) the students were prompted with a second saturated solution of $\text{Sr}(\text{OH})_2$ that is prepared in $\text{Sr}(\text{NO}_3)_2(aq)$, rather than pure water. Students must assess whether the value of $[\text{OH}^-]$ in the second solution is greater than, less than, or the same as the value of $[\text{OH}^-]$ in the first solution. Students must consider the impact on the equilibrium conditions if the $\text{Sr}(\text{OH})_2$ was to be added to a solution already containing $\text{Sr}^{2+}(aq)$ ions, as compared to the original solution where $\text{Sr}(\text{OH})_2$ was added to pure water (SPQ-5.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 7 was 2.23 out of a possible 4 points, with a standard deviation of 1.45 points. The distribution of scores on this question is shown below.



Part (a) was an accessible point for the majority of students. Most students were able to interpret that the particulate diagram should represent the stoichiometric relationship shown by the chemical formula of $\text{Sr}(\text{OH})_2$.

Part (b)(i) was another point that the majority of students were able to earn. Students successfully recognized that $[\text{OH}^-] = 2[\text{Sr}^{2+}]$.

Most students were able to perform the calculation in part (b)(ii), recognizing that the K_{sp} expression provided in Question 7 could be used to mathematically determine the value of K_{sp} , by incorporating the $[\text{Sr}^{2+}]$ given in part (b) and the calculated value of $[\text{OH}^-]$ from part (b)(i) into the expression.

The most difficult point in Question 7 was part (c). Students struggled to provide clear and appropriate explanations for the $[\text{OH}^-]$ in the presence of a common ion relative to the $[\text{OH}^-]$ in water.

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

Common Misconceptions/Knowledge Gaps	Responses that Demonstrate Understanding
<p>Part (a)</p> <ul style="list-style-type: none"> Many responses did not provide a clear explanation. For example, a common answer was to correctly state that the number of ions in the diagram is incorrect, but this answer is incomplete. Some responses would state that the number of ions shown was incorrect, but they failed to provide the correct mole ratio of Sr^{2+} to OH^-. 	<p>Part (a)</p> <ul style="list-style-type: none"> Stating that the Sr^{2+} to OH^- ratio was supposed to be 1:2, but the diagram has equal numbers of each type of ion. Stating that the diagram could be corrected by adding twice the number of OH^- or by decreasing the number of Sr^{2+} by two.
<p>Part (b)(i)</p> <ul style="list-style-type: none"> Students did not utilize the mole relationship between the $[\text{Sr}^{2+}]$ and the $[\text{OH}^-]$ when determining the $[\text{OH}^-]$. The following are examples of incorrect calculations completed by students: <ul style="list-style-type: none"> $[\text{OH}^-] = [\text{Sr}^{2+}]^2$ $[\text{OH}^-] = [\text{Sr}^{2+}]/2$ $[\text{OH}^-] = [\text{Sr}^{2+}]$ Another common error was using K_w to find $[\text{OH}^-]$. Some responses calculated the value of pOH and reported that value as $[\text{OH}^-]$. 	<p>Part (b)(i)</p> <ul style="list-style-type: none"> Many students correctly calculated that $[\text{OH}^-] = 2(0.043 \text{ M}) = 0.086 \text{ M}$
<p>Part (b)(ii)</p> <ul style="list-style-type: none"> A common error in the calculation was forgetting to square the value $[\text{OH}^-]$. A frequent algebraic error was using the incorrect order of operations for the problem. (e.g., $K_{sp} = (0.043)(2)(0.043)^2$) 	<p>Part (b)(ii)</p> <ul style="list-style-type: none"> $K_{sp} = [\text{Sr}^{2+}][\text{OH}^-]^2 = (0.043)[(2)(0.043)]^2 = 3.2 \times 10^{-4}$ $K_{sp} = [\text{Sr}^{2+}][\text{OH}^-]^2 = (0.043)(0.086)^2 = 3.2 \times 10^{-4}$ $K_{sp} = 4x^3 = 3.2 \times 10^{-4}$

<p>Part (c)</p> <ul style="list-style-type: none"> • A common incorrect response included using the rate of the reverse reaction to explain the change in equilibrium position for this situation. The setup compares the preparation of a saturated solution of $\text{Sr}(\text{OH})_2$ in water versus $\text{Sr}(\text{NO}_3)_2(aq)$, and NOT the addition of $\text{Sr}(\text{NO}_3)_2$ to a system already at equilibrium. The extent of dissolution is reduced by the presence of a common ion, not the disturbance of an established equilibrium. • Incorrectly stating that the introduction of the common ion changed the value of the K_{sp}. • Incomplete statements were common, such as solely stating “the common-ion effect” or “Le Chatelier’s principle” without any explanation. This does not provide a valid justification that indicates understanding of equilibrium principles. 	<p>Part (c)</p> <ul style="list-style-type: none"> • A strong answer made three statements: 1) there was less $[\text{OH}^-]$ in the second solution, 2) the Sr^{2+} ion was a common ion and would influence the equilibrium position, and 3) the presence of the Sr^{2+} in the solution initially would reduce the solubility of the $\text{Sr}(\text{OH})_2$ and therefore reduce the $[\text{OH}^-]$ in the second solution at equilibrium when compared to the solution made with pure water. • Students recognized that adding $\text{Sr}(\text{NO}_3)_2$ to the water introduced the common ion of $\text{Sr}^{2+}(aq)$ to the $\text{Sr}(\text{OH})_2$ equilibrium.
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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 the need to be careful in the transcription of numbers that have decimals, especially those with leading zeros (like in 0.043). It is easy to omit the “0” after the decimal and end up with 0.43 and carry that number forward into calculations. These were common errors on this question.
2. Encourage students to read the prompts carefully and critically so that they understand the chemical system(s) being presented and construct their responses appropriately. In terms of the relationship between rate and equilibrium position, comparing the relative rates of the forward and reverse reactions does not address the final position of equilibrium of $\text{Sr}(\text{OH})_2$ in two different solvents. In both systems, equilibrium will be reached when the forward rate equals the reverse rate. However, the equilibrium position of the system with the higher initial concentration of $\text{Sr}^{2+}(aq)$ [the common ion] will be further to the left than in the system that contains only pure water.

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 3.8, 7.11, and 7.12.
- Teachers can use AP Classroom to direct students to the AP Exam On-Demand Reviews: [2022 Session 3: \$K_{sp}\$, \$Q_{sp}\$, and Solubility](#) and [2022 Session 4: Equilibrium Multiple-Choice and Free-Response Questions](#).
- Teachers can have students explore the ratios between dissolved and undissolved particles for slightly soluble salts using the “Design a Salt” tab on the PhET simulation [Salts & Solubility](#).

- Teachers can assign topic questions and/or progress checks in AP Classroom to monitor student progress and identify areas that need additional instruction or content and skill development. Teachers can also create custom quizzes from previously administered AP exam items from the Question Bank to help students practice and refine their understanding of key topics.