

Chief Reader Report on Student Responses: 2018 AP[®] Chemistry Free-Response Questions

• Number of Students Scored	161,852		
• Number of Readers	360		
• Score Distribution	Exam Score	N	%At
	5	21,624	13.4
	4	28,489	17.6
	3	40,285	24.9
	2	38,078	23.5
	1	33,376	20.6
• Global Mean	2.80		

The following comments on the 2018 free-response questions for AP[®] Chemistry were written by the Chief Reader, Paul Bonvallet of the College of Wooster. 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: Analysis of redox experiments

Topics: Oxidation number, stoichiometry, thermochemistry

Max. Points: 10

Mean Score: 4.47

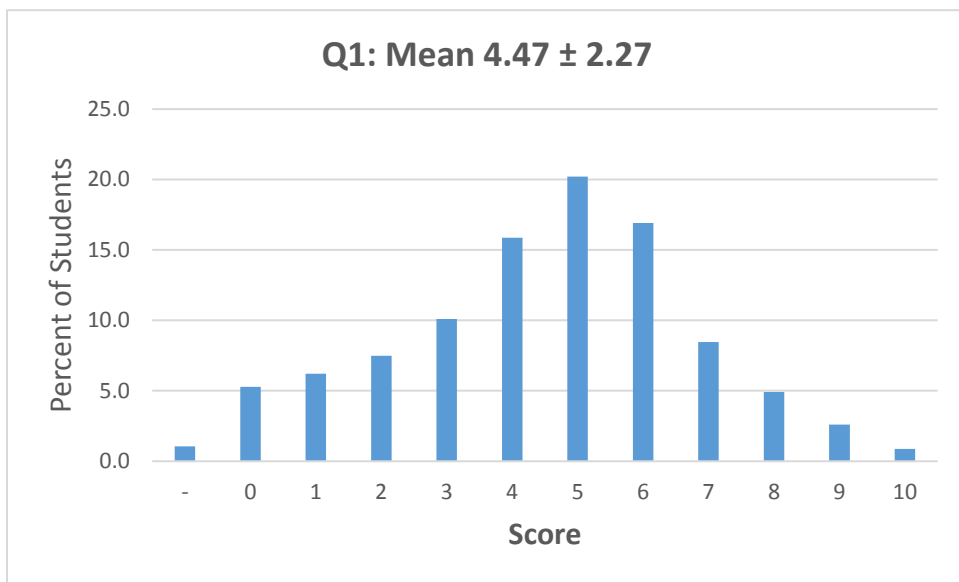
What were the responses to this question expected to demonstrate?

Parts (a) through (c) explored fundamental concepts including oxidation numbers, stoichiometry, and limiting reactants within the context of an oxidation-reduction reaction. In the second grouping, parts (d) through (f) focused on the interpretation of calorimetry data for the redox reaction by determining the standard enthalpy change of the reaction, ΔH°_{rxn} . Part (g) explored student understanding of net-ionic equations.

Students were asked in part (a) to determine the oxidation number of the chlorine atom in NaOCl (LO 3.8; SP 6.1). In part (b) students were asked to determine the mass of $\text{Na}_2\text{S}_2\text{O}_3$ necessary to prepare 100.00 mL of a solution of given concentration (LO 1.4; SP 7.1). In part (c) students were asked to determine the limiting reactant in the reaction, given the balanced chemical equation and the concentrations and volumes of solutions of each reactant (LO 3.4; SP 2.2, 5.1, 6.4). Part (d) asked students to interpret a graph of temperature versus time to determine the temperature change of the reaction mixture (LO 3.1; SP 1.5, 7.1). This answer carries forward to part (e)(i), where students were asked to calculate the magnitude of the heat energy released during the reaction (LO 5.7; SP 4.2, 5.1, 6.4). In part (e)(ii) students were asked to calculate the standard enthalpy change for the reaction (LO 5.7; SP 4.2, 5.1, 6.4). In part (f) students were asked to explain why the calculated value of ΔH°_{rxn} remains unchanged in a second experiment where the volume of each solution of reactant was doubled (LO 3.3; SP 2.2, 5.1). In part (g) students were asked to provide a balanced net-ionic equation for the reaction (LO 3.2; SP 1.5, 7.1).

How well did the response 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 4.47 out of a possible 10 points. The distribution of points on this question is shown below.



Nearly every student attempted Question 1. Most earned at least a few points. The first half of the question, parts (a)-(e)(i), was fairly accessible. Most students earned points in parts (b), (d), and (e)(i). In part (b), most students were able to determine the number of moles of $\text{Na}_2\text{S}_2\text{O}_3$ required and convert this number into grams of $\text{Na}_2\text{S}_2\text{O}_3$. Most students correctly interpreted the graph in part (d) to determine the value of ΔT and then successfully used this result to determine $|q|$ in part (e)(i).

Parts (a) and (c) were more challenging. In part (a), some students assumed that NaOCl contains a chloride ion and thus reported the oxidation number of the chlorine atom as -1. Part (c) required students to evaluate tabular data to determine the limiting reactant. Many students correctly chose NaOCl, although some provided insufficient justification for their choice. The second half of the question, parts (e)(ii)-(g), proved challenging for many students. Parts (e)(ii) and (f) required higher-level thinking and a stronger intuitive understanding of chemical principles. Some students struggled to find a valid method for converting q to ΔH°_{rxn} in part (e)(ii), while many others gave their answer without a negative sign to indicate that the reaction is exothermic. In part (f), many students had difficulty relating the concept of proportionality to ΔH°_{rxn} and did not address the fact that the *ratio* of heat energy released per moles of reactant was unchanged in the second experiment. In part (g), most students failed to provide a complete, balanced, net-ionic equation. Many responses failed to dissociate the sodium salts or otherwise included sodium ion in the equation.

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> <p>Claiming -1, the charge of a chloride ion.</p> <p>Multiplying the oxidation number by the stoichiometric coefficient of NaOCl in the balanced chemical equation.</p> <p>Reporting the number of valence electrons in chlorine.</p>	<p>The oxidation number of Cl in NaOCl is +1. This information can be deduced from the standard +1 and -2 oxidation numbers of sodium and oxygen, respectively.</p>
<p>Part (b):</p> <p>Errors in algebra and/or arithmetic.</p> <p>Incorrect molar mass of Na₂S₂O₃.</p> <p>Expressing molarity in units of g/L, or equating molarity with the number of moles of a substance.</p>	$100.00 \text{ mL} \times \frac{0.500 \text{ mol Na}_2\text{S}_2\text{O}_3}{1000 \text{ mL}} \times \frac{158.10 \text{ g Na}_2\text{S}_2\text{O}_3}{1 \text{ mol Na}_2\text{S}_2\text{O}_3}$ $= 7.90 \text{ g Na}_2\text{S}_2\text{O}_3$

<p>Part (c):</p> <p>Failing to use the information in the table, i.e., claiming NaOCl as the limiting reactant based solely upon its stoichiometric coefficient in the balanced chemical equation.</p> <p>Failing to consider the balanced chemical equation, i.e., claiming that none (or all) of the reactants were limiting because each solution contains the same number of moles of reactant.</p> <p>Choosing NaOCl because it is the reactant with the lowest molar mass.</p> <p>Claiming that an equal number of moles of each reactant was present based only upon the solutions' equal concentrations <u>or</u> equal volumes, rather than using both concentration <u>and</u> volume.</p>	<p>NaOCl is the limiting reactant. Given that equal numbers of moles of each reactant were present initially, it follows from the coefficients of the reactants in the balanced equation that NaOCl will be depleted first.</p>
<p>Part (d):</p> <p>Reading the y-axis tick marks incorrectly, resulting in an incorrect initial and/or final temperature.</p> <p>Rounding to the nearest $\pm 1^\circ\text{C}$ rather than $\pm 0.1^\circ\text{C}$.</p> <p>Reporting ΔT as -12.5°C rather than $+12.5^\circ\text{C}$.</p> <p>Determining that $\Delta T = 12.5^\circ\text{C}$, but then adding 273 to that result to get an answer of 285.5 K.</p>	<p>From the graph the final temperature is 32.5°C.</p> $\Delta T = T_f - T_i = 32.5^\circ\text{C} - 20.0^\circ\text{C} = 12.5^\circ\text{C}$
<p>Part (e)(i):</p> <p>Expressing ΔT in units of Kelvins, which does not match the units of $^\circ\text{C}$ in the specific heat.</p> <p>Assuming ΔT to be 20.0°C (the initial temperature) instead of 12.5°C.</p> <p>Errors in algebraic manipulation.</p>	$q = mc\Delta T = (15.21 \text{ g})(3.94 \text{ J}/(\text{g}\cdot^\circ\text{C}))(12.5^\circ\text{C})$ $= 749 \text{ J}$

<p>Part (e)(ii):</p> <p>Neglecting to make ΔH°_{rxn} negative to indicate an exothermic reaction.</p> <p>Failing to convert q to kJ before solving for ΔH°_{rxn}.</p> <p>Multiplying mol_{rxn} and q rather than using division.</p> <p>Failing to adjust for NaOCl stoichiometry, or adjusting incorrectly (e.g. multiplying by 4 or dividing by the sum of the stoichiometric coefficients of all reactants).</p> <p>Calculating mol_{rxn} from the total mass of the reaction mixture, or from the sum of the molar masses of all reactants.</p> <p>Calculating a second value of q using a different ΔT and/or mass, then subtracting this result from the first value of q from part (e)(i).</p> <p>Attempting to calculate ΔH°_{rxn} from bond dissociation enthalpies or standard enthalpies of formation of reactants and products.</p>	$n_{\text{NaOCl}} = 5.00 \text{ mL} \times \frac{0.500 \text{ mol NaOCl}}{1000 \text{ mL NaOCl}} = 0.00250 \text{ mol NaOCl}$ $n_{rxn} = 0.00250 \text{ mol NaOCl} \times \frac{1 \text{ mol}_{rxn}}{4 \text{ mol NaOCl}} = 0.000625 \text{ mol}_{rxn}$ <p>Divide q by mol_{rxn} and make negative to indicate an exothermic reaction:</p> $\Delta H^\circ_{rxn} = -q / \text{mol}_{rxn} = -0.749 \text{ kJ} / 0.000625 \text{ mol}_{rxn}$ $= -1.20 \times 10^3 \text{ kJ/mol}_{rxn}$
<p>Part (f):</p> <p>Giving an incomplete explanation, e.g., stating only that ΔH°_{rxn} is an intensive property or that ΔH°_{rxn} is independent of solution volume.</p> <p>Failing to indicate that both the number of moles and the heat evolved will double in the second experiment.</p>	<p>By doubling the volumes, the number of moles of the reactants are doubled, which doubles the amount of energy produced. Therefore, the amount of heat per mole will remain the same.</p>

<p>Part (g):</p> <p>Failing to balance with respect to mass and/or charge.</p> <p>Including spectator ions.</p> <p>Using incorrect ionic charges. Sulfate and thiosulfate ions were often assigned a charge of -1.</p> <p>Breaking down polyatomic ions into elemental ions, e.g., writing sulfate ion as $S^{2-} + 4 O^{2-}$.</p>	$S_2O_3^{2-}(aq) + 4 OCl^-(aq) + 2 OH^-(aq) \rightarrow 2 SO_4^{2-}(aq) + 4 Cl^-(aq) + H_2O(l)$
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Based on your experience at the AP[®] Reading with student responses, what advice would you offer to teachers to help them improve the student performance on the exam?

- Require students to show all work and include units, even in intermediate steps, in all calculations.
- Have students perform calculations where some data is read from a graph or table.
- Emphasize the similarities and differences between q (amount of thermal energy absorbed or released in a given situation) versus ΔH°_{rxn} (standard enthalpy change for a reaction). Pay attention to sign conventions in these two values.
- Reinforce the concept of “per mole reaction” and its application in thermochemistry problems.
- Practice writing net-ionic equations for chemical reactions, helping students to recognize the ionic charge of common polyatomic ions.

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

- Teachers will find sample student responses to exam questions on the exam information page on AP Central, along with specific commentary explaining why each point was or was not earned. Teachers can use these samples to work with students to help them become more comfortable in practicing and producing responses within the suggested response time, so that students devote an appropriate amount of time for each question.
- Teachers will find scoring guidelines explaining how the exam questions were scored on the exam information page on AP Central. Teachers can use and adapt these scoring guidelines throughout the AP year so that students become familiar with how their responses will be scored.
- Teachers can review elements of Q1 from the 2017 exam, Q3 from the 2016 exam, and Q2 from the 2015 exam and Q5 and Q6 from the 2014 exam.
- Teachers can use the guidebook *Quantitative Skills in the AP Sciences* (2018) to assist students in developing quantitative skills throughout the course.
- The AP Chemistry Online Teacher Community is active and there are many discussions concerning teaching tips, techniques, and activities that many teachers have found helpful. It is easy to sign up for and you can search topics of discussions from all previous years.
- Newer teachers (and career changers) might want to consider signing up for an APSI. An APSI is a great way to gain in-depth teaching knowledge on AP Chemistry curriculum and exam and is also a great way to network with colleagues from around the country.
- The Chief Reader Report Module is a brief walkthrough of the highlights of the chief reader report, by Paul Bonvallet of the College of Wooster.

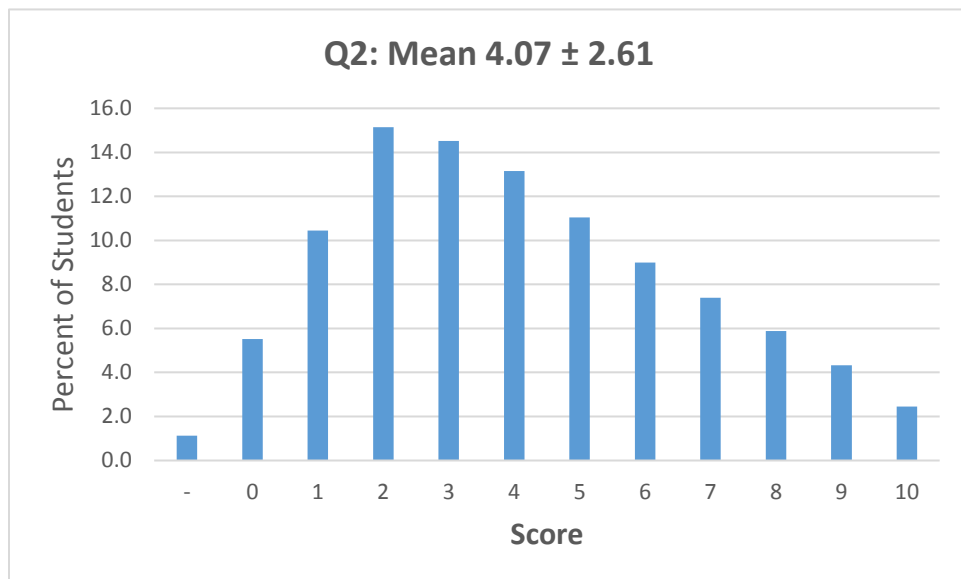
Question #2**Task:** Analysis of reactions of nitrogen oxides**Max. Points:** 10**Topics:** Equilibrium, thermodynamics, Lewis structures, acid-base titration**Mean Score:** 4.07***What were the responses to this question expected to demonstrate?***

Parts (a) through (f) assessed students' understanding of equilibrium, thermodynamics, Le Chatelier's principle, Lewis electron-dot structures, hybridization, acid-base neutralization, and titration.

In part (a) students were asked to draw a particle-level representation of the mixture of NO and O₂ reactants that would afford the product mixture illustrated in the diagram. Students were required to interpret and use the pictorial symbols, making connections between the balanced chemical equation and the particulate diagram (LO 1.17; SP 1.5). In part (b) students were required to use a table of thermodynamic data to calculate the value of the equilibrium constant for an equimolar mixture of NO and NO₂ that has reached equilibrium at 298 K. Students were expected to recognize the relationship between ΔG° and K (LO 6.25; SP 2.3). They were then asked to determine if the partial pressure of N₂O₃ product at equilibrium will be equal to 1.0 atm if the partial pressures of the reactants (NO and NO₂) in the vessel were initially 1.0 atm. The students should recognize that $K < 1$, and thus the partial pressure of N₂O₃ product at equilibrium is greater than 1 atm due to the substantial amount of reactants remaining (LO 6.6; SP 2.2, 6.4). In part (c) students were asked to make and justify a claim about the amount of N₂O₃ product as the temperature is increased. The students should use a qualitative rationale based on the sign of the standard enthalpy change ($\Delta H^\circ < 0$) and Le Chatelier's principle (LO 6.8; SP 1.4, 6.4). In part (d) students were asked to draw the Lewis electron-dot diagram of HNO₂ from the skeletal structure. They were then asked to identify the hybridization of the nitrogen atom in the molecule that they drew (LO 2.21; SP 1.4). In part (e) the students were given a neutralization reaction between HNO₂ and KOH and the corresponding titration curve. They were asked to determine the initial concentration of the HNO₂ solution (LO 1.20; SP 4.2, 5.1, 6.4) and to estimate the pK_a of HNO₂ (LO 6.13; SP 5.1, 6.4). In part (f) the students were asked to determine the major species present after a volume of 15 mL of 0.100 M KOH(aq) had been added during the titration experiment (LO 6.17; SP 6.4). This question required students to recognize that 15 mL of KOH solution is past the half-equivalence point, and thus conclude that NO₂⁻(aq) is the major species.

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 4.07 out of a possible 10 points. The distribution of points on this question is shown below.



Most students scored well on part (a), recognizing the four-molecule excess of NO and drawing the correct particulate representation of the NO and O₂ reactants. Students who earned one out of two possible points either correctly drew representations of NO and O₂ or correctly represented the conservation of atoms. Student performance on part (b) was much weaker. In part (b)(i), students used a variety of mathematical equations that contained ΔG° but were inapplicable to this problem. Many responses had problems with units stemming from the incorrect version of R and/or failing to convert from kJ/mol to J/mol in the intermediate work. Some neglected the negative sign in $-RT \ln K$. In part (b)(ii), many students misunderstood or failed to adequately articulate the conceptual connection between the value of K and the final pressure of the mixture at equilibrium. Even though a short qualitative argument was sufficient for credit, many students performed extensive calculations to determine the exact numerical pressure of N₂O₃ at equilibrium. The point was awarded if the calculation was carried out correctly. In part (c), students often scored well and showed a strong command of the conceptual connection between exothermic reactions and the effect of raising the temperature. Students generally applied Le Chatelier's principle appropriately here.

Student performance was strong on part (d)(i), but weaker on part (d)(ii). Students did well when drawing a valid Lewis structure, but had difficulty interpreting that structure in the context of hybridization. A surprising number of students left part (d)(ii) blank.

As in past years, students struggled with the interpretation of titration data. In part (e)(i), it was possible for students to earn the point by following a circuitous path that involved calculating the initial HNO₂ concentration from the initial pH of the solution, but only if they recognized nitrous acid as a weak acid and estimated its pK_a correctly. Many assumed that nitrous acid was a strong acid, perhaps due to its structural similarity to nitric acid. Students scored well on part (e)(ii) and showed a strong grasp of the significance of the half-equivalence point. Part (f) was much more challenging. The question required students to interpret the graphical data and connect it to the extent to which the acid-base neutralization reaction had proceeded. A number of students failed to recognize that $pH = pK_a$ at the half-equivalence point. Many calculated the exact values of [HNO₂] and [NO₂⁻], which is a valid but time-consuming approach.

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> <p>Drawing species that were not part of the chemical reaction (e.g., monoatomic oxygen, diatomic nitrogen).</p> <p>Improper scale of reaction (incorrect number of the correct reactants).</p> <p>Failure to account for the excess of NO₂.</p>	<p>Drawing a particle-level representation showing 8 molecules of NO and 2 molecules of O₂.</p>
<p>Part (b)(i):</p> <p>Using an equation other than $\Delta G^\circ = -RT \ln K$.</p> <p>Using a value of R that did not contain units of energy.</p> <p>Energy unit inconsistency (kJ vs J) in the values of ΔG° and R.</p>	<p>$\Delta G^\circ = -RT \ln K$</p> <p>$K = e^{-\Delta G^\circ / RT}$</p> $K = e^{-\frac{870 \text{ J/mol}}{(8.314 \text{ J mol}^{-1} \text{ K}^{-1})(298 \text{ K})}}$ <p>$K = 0.70$</p>
<p>Part (b)(ii):</p> <p>Failing to realize (or effectively articulate) the significance of the value of K in relation to the amounts of products and reactants at equilibrium.</p> <p>Using extensive mathematical calculations when a simpler qualitative approach would suffice.</p>	<p>No, the pressure will not equal 1 atm.</p> <p>$P_{\text{N}_2\text{O}_3}$ would only equal 1 atm if the reaction goes to completion.</p> <p>OR</p> <p>The value of K indicates that a substantial amount of reactants will be present at equilibrium.</p>
<p>Part (c):</p> <p>Failing to recognize (or effectively articulate) the effect of increasing temperature on an exothermic reaction at equilibrium.</p> <p>Focusing on ΔG° or ΔS° instead of ΔH°.</p> <p>Arguments about the influence of temperature on the kinetics of the reaction.</p>	<p>Disagree.</p> <p>Because the reaction is exothermic, increasing the temperature of the reaction will favor the formation of the reactants (according to Le Chatelier's principle).</p>

<p>Part (d)(i):</p> <p>Incorrect number of valence electrons.</p> <p>Octet rule violations.</p> <p>Unpaired electrons.</p> <p>Rearranging atoms, in contradiction of the given H—O—N—O framework.</p>	<p>Using the correct number of valence electrons, with all electrons paired and no octet violations.</p> <p>Recognizing that when the question provides a skeletal structure of atomic connectivity, the atoms should not be rearranged.</p>
<p>Part (d)(ii):</p> <p>Incorrect counting of electron domains.</p> <p>Reporting the geometry or electron configuration of nitrogen, rather than the hybridization.</p>	<p>sp^2</p>
<p>Part (e)(i):</p> <p>Assuming that nitrous acid is a strong acid, then substituting the initial pH in the expression $[\text{HNO}_2] = 10^{-\text{pH}}$.</p>	<p>$20. \text{ mL KOH} \times \frac{0.100 \text{ mol KOH}}{1000 \text{ mL KOH}} = 0.0020 \text{ mol KOH added}$ $\Rightarrow 0.0020 \text{ mol HNO}_2$ in 100. mL of solution because the stoichiometry of the neutralization reaction is 1 to 1.</p> $\frac{0.0020 \text{ mol HNO}_2}{0.100 \text{ L}} = 0.020 \text{ M HNO}_2$
<p>Part (e)(ii):</p> <p>Estimating $\text{p}K_a$ from the pH at the equivalence point, rather than at the half-equivalence point</p>	<p>The value of $\text{p}K_a$ is about 3.4.</p>
<p>Part (f):</p> <p>Claiming that any time a solution pH is less than 7, the dominant species must be the weak acid.</p>	<p>$\text{NO}_2^-(aq)$</p> <p>The titration is past the half-equivalence point, therefore there will be more conjugate base present than acid.</p>

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

1. Give students opportunities to interpret particulate diagrams to enhance their conceptual understanding of stoichiometry and mass balance.
2. Encourage students to always include units with every numerical quantity they use. This practice will help avoid simple mistakes like using a version of the gas constant R that has incompatible units.
3. Contrast kinetic outcomes versus thermodynamic ones in the context of equilibrium and reactions going to completion. Likewise, clarify the difference between reactions at equilibrium versus reactions that go fully to completion.
4. Students should practice identifying electron domains and their relationship to hybridization. Many students seem to misunderstand the term “hybridization” and the method for counting electron domains.
5. Ask students to articulate what happens to the analyte and titrant at each point in a titration experiment. Clarify the meaning of, and differences between, the equivalence point and 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 will find sample student responses to exam questions on the exam information page on AP Central, along with specific commentary explaining why each point was or was not earned. Teachers can use these samples to work with students to help them become more comfortable in practicing and producing responses within the suggested response time, so that students devote an appropriate amount of time for each question.
- Teachers will find scoring guidelines explaining how the exam questions were scored on the exam information page on AP Central. Teachers can use and adapt these scoring guidelines throughout the year so that students become familiar with how their responses will be scored.
- Teachers can review elements of Q2, Q3, Q5 and Q6 from the 2017 exam, Q1 from the 2016 exam, and Q1, Q2 and Q7 from the 2015 exam and Q6 from the 2014 exam.
- Teachers can use the guidebook *Quantitative Skills in the AP Sciences* (2018) to assist students in developing quantitative skills throughout the course.
- The AP Chemistry Online Teacher Community is active and there are many discussions concerning teaching tips, techniques, and activities that many teachers have found helpful. It is easy to sign up for and you can search topics of discussions from all previous years.
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Question #3

Task: Analysis of reactions of iron
Max. Points: 10

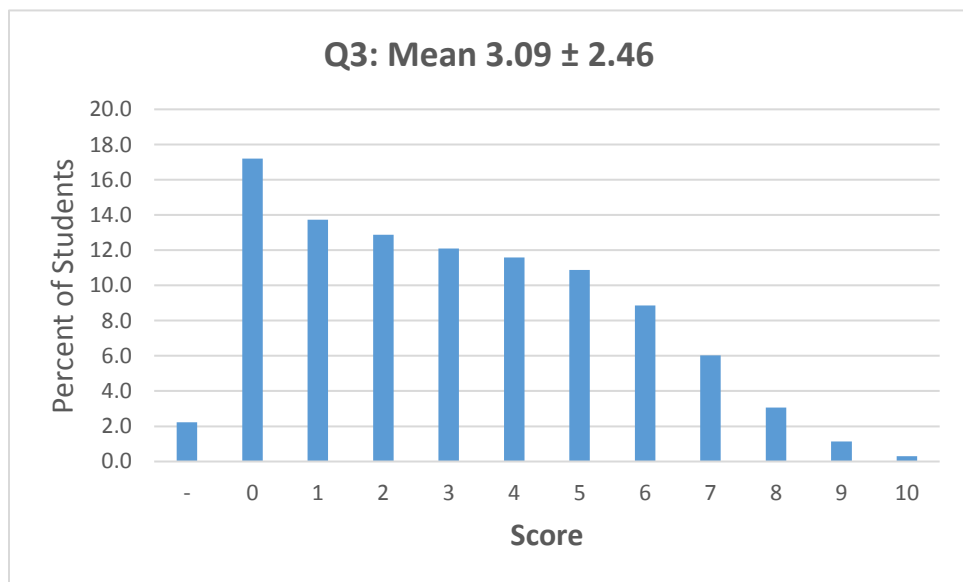
Topic: Redox reactions and mass percent composition
Mean Score: 3.09

What were the responses to this question expected to demonstrate?

This question used the properties and reactions of iron and iron ions to assess students' mastery of atomic structure and reaction stoichiometry. It dealt broadly with qualitative and quantitative connections between experimental observations and atomic/molecular/bulk structure. Students were asked in parts (a) through (c) to use principles of atomic structure to predict the electron configuration of Fe^{2+} (LO 1.19; SP 6.4) and explain differences in its ionic radius (LO 1.19; SP 6.4) and the strength of its Coulombic interaction with water molecules in comparison to Fe^{3+} (LO 1.10; SP 6.1). Part (d) asked students to write a balanced half-reaction for the oxidation of Fe^{2+} to Fe^{3+} (LO 3.13; SP 5.1), and then part (e) had them calculate $[\text{Fe}^{2+}]$ based upon the results of a redox titration (LO 3.9; SP 4.2, 5.1). The students then needed to justify in part (f) why a 25 mL volumetric flask would be a poor choice for dispensing 10.00 mL of Fe^{2+} solution (LO 3.9; SP 4.2, 5.1). The students were asked in part (g) in a separate experiment to calculate the number of moles of Fe present in a sample containing an inert impurity (LO 1.4; SP 7.1) and then in part (h) to determine the percent by mass of Fe present in the original sample (LO 1.2; SP 2.2). Part (i) was an error analysis question that probed students' understanding of the impact of an incomplete oxidation reaction on the quantitative outcome of the experiment (LO 1.2; SP 2.2).

How well did the response 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 3.09 out of a possible 10 points. The distribution of points on this question is shown below.



Students often incorrectly answered part (a) as $[\text{Ar}]4s^23d^4$, highlighting a misunderstanding of the subtle difference between the order of orbital filling versus the order of electron removal in forming ions of transition metals. Responses to part (b) usually followed the correct general line of thinking, although some had insufficient detail to merit credit. In part (c), students seemed conceptually familiar with Coulomb's law. However, some failed to earn the point because of the mistaken belief that the "distance" term in the Coulomb's law expression referred to atomic radius rather than the distance between an iron atom and a water molecule. It was not necessary to define or write the Coulomb's law expression explicitly to receive credit. Student responses to part (d) revealed a basic understanding of reduction half-reactions. It was necessary to balance both mass and electronic charge to earn credit.

Stoichiometric conversion factors appeared in both parts (e) and (g). Students who took the care to show full unit labels in all intermediate work often received full credit for these parts, whereas those who did not show unit labels were generally less successful. In part (f), a sizeable population of students seemed unfamiliar with what a volumetric flask is. It is possible that students do have experience using a volumetric flask, but may not have known what it is called. The stoichiometric calculations in parts (e) and (g) were straightforward for most students, with the calculation of mass percent of iron in part (h) being more challenging but still accessible. Error analysis continues to be challenging for students, as evidenced by the low instance of credit for part (i). This part required students to be clear both in their thinking and in their writing to receive credit.

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> <p>Removing electrons from the incorrect orbitals, or not removing electrons at all, as in:</p> <p>$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^4$</p> <p>$1s^2 2s^2 2p^6 3s^2 3p^6 4s^1 3d^5$</p> <p>$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^6$</p>	<p>The electron configuration of Fe^{2+} is $1s^2 2s^2 2p^6 3s^2 3p^6 3d^6$, which can also be written $[\text{Ar}] 3d^6$.</p>
<p>Part (b):</p> <p>Stating that the Fe^{3+} nucleus has one more proton than the Fe^{2+} nucleus.</p> <p>Claiming that ionic radius is determined solely by the number of valence electrons in the ion (i.e., stating “Fe^{2+} has more electrons” without any further explanation).</p> <p>Using the phrase “effective nuclear charge” as the entire answer, in the absence of any additional details to show evidence of understanding in a full explanation.</p>	<p>Both ions have the same nuclear charge.</p> <p>However, the greater number of electrons in the outermost shell of Fe^{2+} results in greater electron-electron repulsion within that shell, leading to a larger radius.</p>

<p>Part (c):</p> <p>Claiming that the denominator in the Coulomb's law expression represented the distance between an iron ion nucleus and the outermost electron, rather than the distance between the iron ion and a water molecule.</p>	$F \propto \frac{q_1 q_2}{\text{distance}^2}$ <p>In comparison to the Fe^{2+} ion, the Fe^{3+} ion has a higher charge.</p> <p>OR</p> <p>The smaller size of Fe^{3+} allows it to get closer to a water molecule.</p> <p>Arguing either a "greater numerator" or a "smaller denominator" in the Coulomb's law expression was sufficient to earn credit. It was not necessary to define or write Coulomb's law explicitly.</p>
<p>Part (d):</p> <p>Subtracting electrons from reactants, rather than adding them to products.</p> <p>Neglecting to balance total charge, most commonly as:</p> $\text{Fe}^{2+} + e^- \rightarrow \text{Fe}^{3+} \text{ or}$ $5 \text{Fe}^{2+} \rightarrow 5 \text{Fe}^{3+} + e^-$	<p>$\text{Fe}^{2+} \rightarrow \text{Fe}^{3+} + e^-$ is balanced with respect to mass and charge.</p> <p>$5 \text{Fe}^{2+} \rightarrow 5 \text{Fe}^{3+} + 5 e^-$ is likewise balanced and received credit.</p>
<p>Part (e):</p> <p>Using the equation $M_1 V_1 = M_2 V_2$ to find moles of iron(II), which neglects the stoichiometric ratio of iron(II) to permanganate ion.</p>	$0.01748 \text{ L} \times \frac{0.0350 \text{ mol KMnO}_4}{\text{L}} = 0.000612 \text{ mol KMnO}_4$ $\times \frac{5 \text{ mol Fe}^{2+}}{1 \text{ mol MnO}_4^-} = 0.003059 \text{ mol Fe}^{2+}$ $\frac{0.003059 \text{ mol Fe}^{2+}}{0.0100 \text{ L}} = 0.306 \text{ M Fe}^{2+}$
<p>Part (f):</p> <p>Making irrelevant statements about the shape of the volumetric flask or the size of its opening.</p> <p>Some students seemed unfamiliar with the term "volumetric flask".</p>	<p>The volumetric flask is designed to contain only 25.00 mL precisely. Its single marking would not allow the user to measure 10.0 mL.</p>
<p>Part (g):</p> <p>Neglecting the 2:1 stoichiometric ratio of Fe to Fe_2O_3.</p>	$7.531 \text{ g Fe}_2\text{O}_3 \times \frac{1 \text{ mol Fe}_2\text{O}_3}{159.70 \text{ g Fe}_2\text{O}_3} = 0.04716 \text{ mol Fe}_2\text{O}_3$ $0.04716 \text{ mol Fe}_2\text{O}_3 \times \frac{2 \text{ mol Fe}}{1 \text{ mol Fe}_2\text{O}_3} = 0.09431 \text{ mol Fe}$ <p>4 significant figures intended; 3-5 significant figures acceptable</p>

<p>Part (h):</p> <p>Calculating percent yield or percent error rather than mass percent.</p> <p>Comparing the calculated mass of Fe to the mass of the oxidized sample, rather than to the mass of the original sample.</p>	$0.09431 \text{ mol Fe} \times \frac{55.85 \text{ g Fe}}{1 \text{ mol Fe}} = 5.267 \text{ g Fe}$ $\frac{5.267 \text{ g Fe}}{6.724 \text{ g sample}} \times 100\% = 78.33\% \text{ Fe by mass}$
<p>Part (i):</p> <p>Confusing the actual amount of Fe₂O₃ produced with the calculated amount of Fe₂O₃ produced, thereby arriving at the reverse of the correct answer.</p> <p>Using vague or ambiguous wording, making it impossible to tell whether the student was discussing the original sample, the fully-oxidized sample, or the partially-oxidized sample.</p>	<p>The calculated mass percent of Fe would be lower than the actual mass percent of Fe.</p> <p>A sample that contains any FeO (rather than Fe₂O₃) will have a higher <u>actual</u> mass percent of Fe than a completely oxidized sample would have. Therefore, when the moles of Fe are calculated (assuming all the mass of the sample is Fe₂O₃) the <u>calculated</u> number of moles of Fe, and hence the <u>calculated</u> mass percent of Fe, will be lower.</p> <p>A full calculation of the mass percent of iron in the partially-oxidized and fully-oxidized samples did receive credit, but was not required.</p>

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

- When forming a transition metal ion, the *s* valence electrons in the highest *n* shell are removed before the *d* electrons in the *n*-1 shell.
- Give students opportunities to apply Coulomb's law in situations beyond effective nuclear charge. Most students did well on part (b) but showed in part (c) that they thought of nucleus-electron attraction as the sole context of Coulombic interaction.
- Discourage mnemonic shortcuts like $M_1V_1 = M_2V_2$ in stoichiometry problems, as this approach neglects to account for the stoichiometric coefficients in the balanced chemical equation.
- All work for calculations must be shown and each value must be labeled with its unit, especially in intermediate work.
- Practice error analysis questions, asking students to predict the specific quantitative outcome of the experiment and to clearly articulate their line of reasoning.

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

- Teachers will find sample student responses to exam questions on the exam information page on AP Central, along with specific commentary explaining why each point was or was not earned. Teachers can use these samples to work with students to help them become more comfortable in practicing and producing responses within the suggested response time, so that students devote an appropriate amount of time for each question.
- Teachers will find scoring guidelines explaining how the exam questions were scored on the exam information page on AP Central. Teachers can use and adapt these scoring guidelines throughout the AP year so that students become familiar with how their responses will be scored.
- Teachers can review elements of Q4 from the 2016 exam, and Q3, Q4 and Q6 from the 2015 exam and Q1, Q2, and Q3 from the 2014 exam.
- Teachers can use the guidebook *Quantitative Skills in the AP Sciences* (2018) to assist students in developing quantitative skills throughout the course.

- The AP Chemistry Online Teacher Community is active and there are many discussions concerning teaching tips, techniques, and activities that many teachers have found helpful. It is easy to sign up for and you can search topics of discussions from all previous years.
- Newer teachers (and career changers) might want to consider signing up for an APSI. An APSI is a great way to gain in depth teaching knowledge on AP Chemistry curriculum and exam and is also a great way to network with colleagues from around the country.
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Question #4

Task: Interpret boiling point data and apply the ideal gas law

Topic: Intermolecular forces and the ideal gas law

Max. Points: 4

Mean Score: 1.87

What were the responses to this question expected to demonstrate?

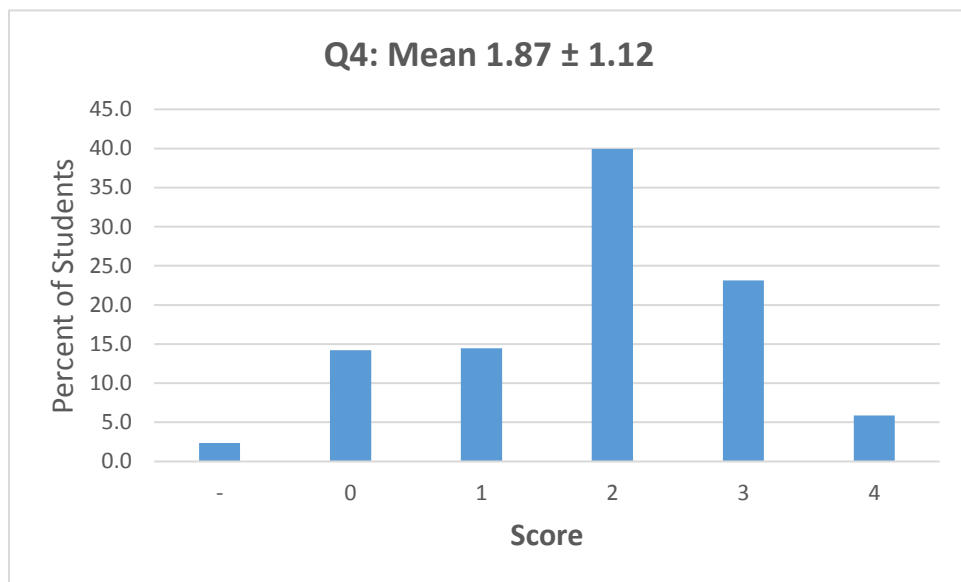
In part (a) the students were required to explain the differences in boiling point between CS_2 and COS in terms of the relative strengths of the intermolecular forces in each compound. In this case, the substance with the higher boiling point only had London dispersion forces, while the other substance had both London dispersion forces and dipole-dipole interactions. (LO 5.11; SP 7.2).

Students were required to recognize that the London dispersion forces between molecules of $\text{CS}_2(l)$ were stronger than the combination of London dispersion and dipole-dipole forces in $\text{COS}(l)$. The London dispersion forces among molecules of $\text{CS}_2(l)$ are stronger because CS_2 has a larger, more polarizable electron cloud than COS . These stronger intermolecular forces increase the boiling point of the substance (LO 2.11; SP 6.2, 6.4).

In part (b) students were asked to use the ideal gas law to calculate the pressure of a gas in a closed container after all the substance had vaporized (LO 2.6; SP 2.2, 2.3). They were required to report the correct value with units that were consistent with the version of R used in the intermediate calculations.

How well did the response 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 1.87 out of a possible 4 points. The distribution of points on this question is shown below.



In part (a), many students were unable to correctly identify the intermolecular forces present in both molecules. They often recognized that the carbon-sulfur bonds in CS_2 are polar, but neglected the cancellation of these bond dipoles in the linear molecule. Most students recognized that the total strength of all intermolecular forces in CS_2 must be greater than the total strength of all intermolecular forces in COS to account for the difference in boiling points. However, many failed to specifically identify that the London dispersion forces between CS_2 molecules were greater than the combined

intermolecular forces in COS. In a few cases, students incorrectly equated boiling point with vapor pressure and thus reversed the correct explanation.

In part (b), most students correctly calculated the number of moles of gas by dividing the mass of CS₂ by the correct molar mass. They were likewise successful in using the ideal gas law to correctly calculate the pressure in the sealed container after all of the substance had vaporized (LO 2.6, SP 2.2).

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> <p>Stating that both CS₂ and COS have only London dispersion forces, or that both have dipole-dipole forces.</p> <p>Implying or explicitly stating that boiling involves the breaking of covalent bonds.</p> <p>Using molar mass as the sole justification of the boiling point trend.</p> <p>Claiming that dipole-dipole interactions are always stronger than London dispersion forces.</p> <p>Equating boiling point with vapor pressure.</p>	<p>CS₂ has only London dispersion forces, while COS has London dispersion forces and dipole-dipole forces.</p> <p>The London dispersion forces in CS₂ are stronger than the combination of London dispersion forces and dipole-dipole forces in COS.</p>
<p>Part (b):</p> <p>Using the incorrect equation, such as $q = mc\Delta T$.</p> <p>Algebraic errors in rearranging $PV = nRT$.</p> <p>Incorrect calculation of number of moles of CS₂ (either dividing molar mass by mass of CS₂, or assuming an arbitrary amount of CS₂ like 1.0 g or 1.0 moles).</p> <p>Using the incorrect temperature, e.g. 319°C.</p> <p>Various errors with the ideal gas constant:</p> <ul style="list-style-type: none"> Using $R = 0.0821$ and reporting pressure without any units. 	$10.0 \text{ g CS}_2 \times \frac{1 \text{ mol CS}_2}{76.13 \text{ g CS}_2} = 0.131 \text{ mol CS}_2$ $P = \frac{nRT}{V} =$ $\frac{(0.131 \text{ mol})(0.08206 \text{ L atm mol}^{-1} \text{ K}^{-1})(325 \text{ K})}{5.0 \text{ L}}$ $= 0.70 \text{ atm}$

- | | |
|---|--|
| <ul style="list-style-type: none">Reporting the pressure in atm after using $R = 8.314 \text{ J mol}^{-1} \text{ K}^{-1}$ or $62.396 \text{ L torr mol}^{-1} \text{ K}^{-1}$. | |
|---|--|

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

- Address common misconceptions, such as: covalent bonds breaking during phase changes, or that the strength of a covalent bond influences boiling point, or that dipole-dipole forces are always stronger than London dispersion forces.
- 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” made it challenging to discern whether they were truly talking about intermolecular forces.
- Encourage students to compare and contrast the ideas of polar bonds versus polar molecules. Molecular geometry can sometimes be critically important in predicting molecular polarity.
- Insist that students use full and complete unit labels in all calculations, even in intermediate work. Students often mismatched their value of R with their units in the final answer of pressure in part (b).

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

- Teachers will find sample student responses to exam questions on the exam information page on AP Central, along with specific commentary explaining why each point was or was not earned. Teachers can use these samples to work with students to help them become more comfortable in practicing and producing responses within the suggested response time, so that students devote an appropriate amount of time for each question.
- Teachers will find scoring guidelines explaining how the exam questions were scored on the exam information page on AP Central. Teachers can use and adapt these scoring guidelines throughout the AP year so that students become familiar with how their responses will be scored.
- Teachers can review elements of Q1, Q2, and Q4 from the 2017 exam, Q5 and Q7 from the 2016 exam, and Q2, Q4 and Q6 from the 2015 exam and Q4, Q6 and Q7 from the 2014 exam.
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Question #5**Task:** Qualitatively and quantitatively describe aspects of weak acid equilibrium**Topic:** Ionization and K_a of HF**Max. Points:** 4**Mean Score:** 1.32***What were the responses to this question expected to demonstrate?***

This question allowed students to demonstrate their understanding of weak acid equilibria in aqueous solution.

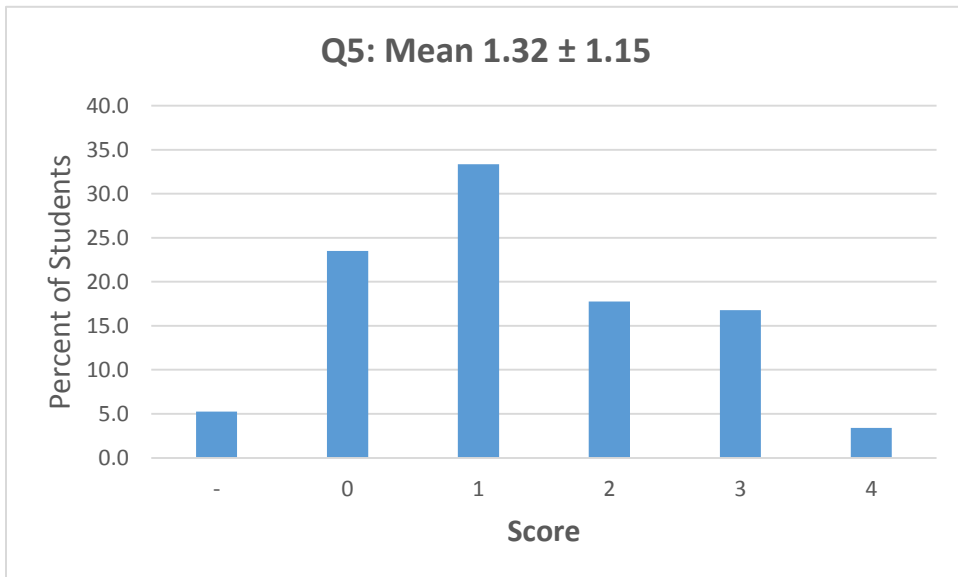
In part (a) students were asked to explain why Figure 1 (a particulate representation showing partial ionization of HF) was better than Figure 2 (a representation showing complete ionization of HF) in describing a 0.0350 M HF(aq) solution with 13.0 percent ionization (LO 6.11; SP 1.1, 1.4, 2.3). Responses could point out either that Figure 1 represented 13.0 percent ionization because 1 out of 8 HF molecules was ionized, or that Figure 2 showed HF to be 100 percent ionized and thus could not represent a weak acid.

In part (b) students were asked to use the percent ionization and the concentration of the HF(aq) to calculate the value of K_a (LO 6.5; SP 2.2). Responses needed to determine $[H_3O^+]$, $[F^-]$, and $[HF]$ from the percent ionization information and then use them correctly in a K_a expression.

In part (c) students were presented with a hypothetical dilution of the original solution by adding 50.0 mL of H_2O to the 0.0350 M aqueous HF solution. They were asked to predict the impact that this dilution would have upon the percent ionization of HF and to justify their choice. The best responses calculated or qualitatively described the instantaneous reaction quotient Q and correctly predicted an increase in the percent ionization of HF because $Q < K_a$ (LO 6.4; SP 2.2, 6.4).

How well did the response 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 1.32 out of a possible 4 points. The distribution of points on this question is shown below.



Responses to part (a) were generally successful in explaining why Figure 1 was a more accurate representation of 13.0% ionized HF than Figure 2. In part (b), most students correctly set up the general K_a expression, but they frequently misinterpreted the mathematical meaning of 13.0% ionization and thus used incorrect values for $[H_3O^+]$ and/or $[HF]$. In

part (c), many students had challenges predicting the direction of change in percent ionization (and articulating the reason for their choice) upon the dilution of the original HF solution. Le Chatelier's principle was frequently used incorrectly, with statements like "increasing the concentration of the water reactant" used to explain the shift in equilibrium towards products. Nevertheless, a fair number of students made successful qualitative or quantitative arguments about the increased percent ionization of HF.

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> <p>Equating the percent ionization with a K_{sp} or percent dissolution.</p> <p>Comparing the extent to which HF undergoes hydrogen bonding.</p>	<p>HF is a weak acid and is only partially ionized. This fact is consistent with Figure 1, which shows that one out of eight (~13%) HF molecules is ionized (to form one H_3O^+ and one F^-).</p> <p>OR</p> <p>Figure 2 cannot represent HF because it represents 100% ionization of the acid.</p>												
<p>Part (b):</p> <p>Interpreting 13.0% ionization as meaning that $[\text{H}_3\text{O}^+]$ and/or $[\text{HF}] = 13.0\text{ M}$ or 0.130 M.</p> <p>Neglecting to perform the subtraction to determine $[\text{HF}]$ (i.e., $0.0350\text{ M} - 0.00455\text{ M}$). Students often assumed that $[\text{HF}]$ remained at 0.0350 M.</p> <p>Assuming that $K_a = [\text{H}_3\text{O}^+]$</p>	<p>Assume that $[\text{H}_3\text{O}^+] = [\text{F}^-]$ in $\text{HF}(aq)$.</p> $\frac{[\text{H}_3\text{O}^+]}{0.0350\text{ M}} = 0.130 \Rightarrow [\text{H}_3\text{O}^+] = 0.00455\text{ M}$ $\text{HF}(aq) + \text{H}_2\text{O}(l) \rightleftharpoons \text{F}^-(aq) + \text{H}_3\text{O}^+(aq)$ <table style="margin-left: auto; margin-right: auto;"> <tr> <td>I</td> <td>0.0350</td> <td>0</td> <td>~0</td> </tr> <tr> <td>C</td> <td>-0.00455</td> <td>+0.00455</td> <td>+0.00455</td> </tr> <tr> <td>E</td> <td>0.0304</td> <td>0.00455</td> <td>0.00455</td> </tr> </table> $K_a = \frac{[\text{H}_3\text{O}^+][\text{F}^-]}{[\text{HF}]} = \frac{(0.00455)^2}{0.0304} = 6.81 \times 10^{-4}$	I	0.0350	0	~0	C	-0.00455	+0.00455	+0.00455	E	0.0304	0.00455	0.00455
I	0.0350	0	~0										
C	-0.00455	+0.00455	+0.00455										
E	0.0304	0.00455	0.00455										
<p>Part (c):</p> <p>Stating that percent ionization is a constant, dictated only by the identity of the weak acid.</p> <p>Equating percent ionization with K_a, and thus stating that $[\text{HF}]$ remains at a constant 13.0% ionization.</p> <p>Using Le Chatelier's principle to claim that the dilution increases the concentration of water and thus shifts the equilibrium towards products.</p>	<p>The percent ionization of HF in the solution would increase.</p> <p>Doubling the volume of the solution decreases the initial concentration of each species by one-half.</p> $\text{Therefore } Q = \frac{(\frac{1}{2}[\text{H}_3\text{O}^+]_i)(\frac{1}{2}[\text{F}^-]_i)}{\frac{1}{2}[\text{HF}]_i} = \frac{1}{2}K_a \Rightarrow Q < K_a$ <p>Consequently the equilibrium position will shift toward the products and increase the percent ionization.</p>												

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

- Provide students with multiple contexts (e.g., particulate diagrams) to evaluate and predict the behavior of weak acids.
- Incorporate the concept of percent ionization into discussions of weak acid equilibria, showing its relationship to $[H^+]$, $[A^-]$, and $[HA]$.
- Emphasize the importance of using equilibrium concentration, rather than initial concentration, in the calculation of K_a and other equilibrium constants.
- Demonstrate how comparing Q versus K complements (and in some cases is more helpful than) Le Chatelier's principle.

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

- Teachers will find sample student responses to exam questions on the exam information page on AP Central, along with specific commentary explaining why each point was or was not earned. Teachers can use these samples to work with students to help them become more comfortable in practicing and producing responses within the suggested response time so that students devote an appropriate amount of time for each question.
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Question #6

Task: Describe the operation of a galvanic cell

Topic: Galvanic cells and electrochemistry

Max. Points: 4

Mean Score: 1.49

What were the responses to this question expected to demonstrate?

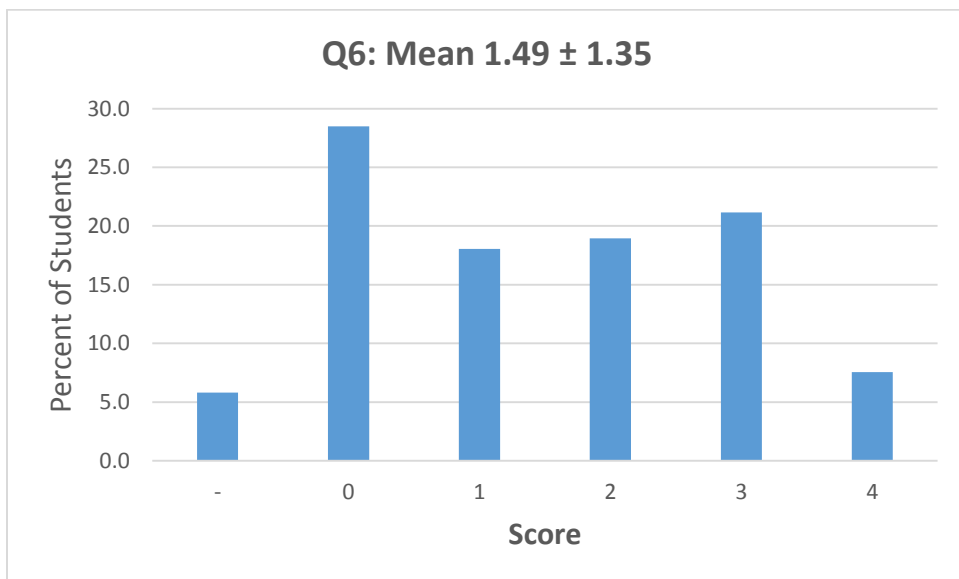
This question required students to identify that the salt bridge was missing and to articulate its role in a standard galvanic cell. They then needed to calculate the standard reduction potential of the anode, given the cathode potential and the overall cell potential. Students were asked to write the balanced net-ionic equation for the overall reaction and then to calculate the standard Gibbs free energy change for the overall cell reaction.

In part (a) a schematic drawing of an electrochemical cell was provided, with the salt bridge omitted. The question asked students to identify the missing component of the cell and to explain its importance for obtaining a nonzero voltage (LO 3.12; SP 2.2, 2.3, 6.4). A correct response to this question required identification of the missing salt bridge and a discussion of its role in allowing for the migration of ions between half-cell compartments. This component is necessary to maintain charge balance during the operation of the cell.

In part (b)(i) students were asked to calculate the value of E° for the standard reduction of Cr^{3+} (LO 3.13; SP 5.1). The question indicated that Ag^+ ions are reduced, so students needed to deduce that chromium is oxidized in the overall cell reaction. In part (b)(ii) the question required the chromium and silver half-reactions from the data table to be combined into a balanced chemical equation appropriate for a galvanic cell (LO 3.2; SP 1.5, 7.1). Finally, in part (b)(iii), the students were asked to calculate the standard Gibbs free energy change for the overall cell reaction (LO 5.14; SP 2.2).

How well did the response 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 1.49 out of a possible 4 points. The distribution of points on this question is shown below.



The first point in this question was awarded the least often. In part (a), most students identified the salt bridge as the missing component, but a substantial number struggled to articulate its function. The most common misconception was that electrons flow through the salt bridge. A number of responses mentioned the presence of ions in the salt bridge, but were incorrect or insufficiently detailed in describing what these ions were doing.

Students were generally successful in part (b), although a number of algebraic and/or algorithmic errors were made in subparts (i) and (iii). Additionally, many errors originated from conceptual misunderstandings regarding the potential of an electrochemical cell; these errors included multiplying the silver half-cell potential by 3 or reversing the oxidation and reduction half-reactions. Similarly, in part (b)(ii), errors in balancing the reaction frequently illustrated a misunderstanding of the principles of redox reactions.

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> <p>Misidentification of the salt bridge.</p> <p>Indicating that electrons flow through the salt bridge.</p> <p>Using vague language to describe the function of the salt bridge, such as “balances charge,” “completes the circuit,” or “neutralizes charge.” These phrases are the beginning of a complete answer, but by themselves do not suffice as a full explanation.</p>	<p>The salt bridge is missing. The salt bridge allows for the migration of ions to maintain charge balance in each half-cell.</p>
<p>Part (b)(i):</p> <p>Multiplying the Ag^+ reduction potential by 3, the stoichiometric coefficient of silver(I) ion in the balanced chemical equation reaction.</p> <p>Misidentifying the reduction potentials at the anode and cathode.</p> <p>Calculating the oxidation potential of chromium (+0.74 V) without converting to a reduction potential.</p> <p>Errors in algebra.</p>	<p>In part (i):</p> $E_{\text{cell}}^{\circ} = E_{\text{red}}^{\circ}(\text{cathode}) - E_{\text{red}}^{\circ}(\text{anode})$ $+1.54 \text{ V} = +0.80 \text{ V} - x$ $x = +0.80 \text{ V} - (+1.54 \text{ V}) = -0.74 \text{ V}$
<p>Part (b)(ii):</p> <p>Reversing the position of the reactants and products, thus making the cell electrolytic rather than galvanic.</p> <p>Omitting the stoichiometric coefficient for silver.</p> <p>Combining two reductive half-reactions, i.e.</p> $\text{Ag}^+ + \text{Cr}^{3+} \rightarrow \text{Ag} + \text{Cr}$ <p>Writing a full equation that includes electrons as reactants or products, e.g., $4\text{e}^- + \text{Ag}^+ + \text{Cr}^{3+} \rightarrow \text{Ag} + \text{Cr}$.</p>	$3 \text{Ag}^+(\text{aq}) + \text{Cr}(\text{s}) \rightarrow 3 \text{Ag}(\text{s}) + \text{Cr}^{3+}(\text{aq})$

<p>Part (b)(iii):</p> <p>Using a value other than $n = 3$ for the number of moles of electrons transferred. Typical values included $n = 2$ or $n = 4$, which came from adding or subtracting the number of electrons shown in the table of standard reduction potentials.</p> <p>Substituting the silver or chromium half-cell potential in place of the overall cell potential of 1.54 V.</p>	$\Delta G_{cell}^{\circ} = -nFE_{cell}^{\circ}$ $= -(3 \text{ mol } e^{-})(96,485 \frac{\text{C}}{1 \text{ mol } e^{-}})(1.54 \frac{\text{J}}{\text{C}})$ $= -4.46 \times 10^5 \text{ J/mol}_{rxn}$
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Based on your experience at the AP[®] Reading with student responses, what advice would you offer to teachers to help them improve the student performance on the exam?

- Encourage students to verbally describe the operating principles of a galvanic cell, focusing on an appropriate level of detail, proper terminology, and precision in language.
- Encourage students to read the question fully. The question states that Ag^+ is reduced in the galvanic cell, yet many responses showed the oxidation of Ag.
- Emphasize the importance of mastering terminology like anode versus cathode and oxidation potential versus reduction potential. Mnemonic devices (e.g., “LEO GER” or “OIL RIG”) can be helpful but must be applied consistently and correctly.
- Review the structure and pace of your course so that electrochemistry is addressed before the date of the AP Chemistry Exam. A small but noticeable population of students stated in their response that they had never seen electrochemistry before.

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

- Teachers will find sample student responses to exam questions on the exam information page on AP Central, along with specific commentary explaining why each point was or was not earned. Teachers can use these samples to work with students to help them become more comfortable in practicing and producing responses within the suggested response time, so that students devote an appropriate amount of time for each question.
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Question #7

Task: Identify an element from PES; calculate radioisotope decay

Max. Points: 4

Topic: Photoelectron spectroscopy and half-life

Mean Score: 2.02

What were the responses to this question expected to demonstrate?

The intent of this question was for students to describe various attributes of nitrogen, from its photoelectron spectrum to the first-order decay of one of its radioisotopes.

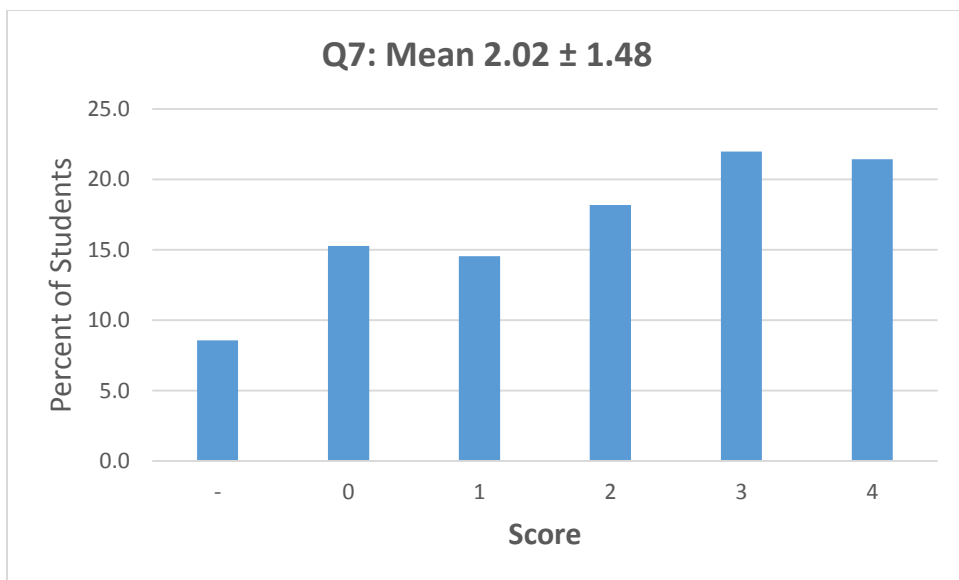
Part (a) presents students with the photoelectron spectrum of an unknown element and asks for the identity of the element (LO 1.5; SP 1.5, 6.2). Students had to realize that the peaks represented different energy sublevels, that electrons in the lowest-energy sublevel had the greatest binding energy, and that the height of the peaks correlated with the number of electrons.

Part (b) of the question assessed students' ability to calculate the rate constant when given the half-life of a radioactive isotope (LO 4.3; SP 2.1, 2.2). Students needed to recognize nuclear decay as a first-order process and then use an appropriate mathematical routine to calculate the value of k (with appropriate units).

Part (c) assessed students' ability to determine the expected amount of time for the radioactive decay, given initial and final numbers of atoms (LO 4.2; SP 5.1, 6.4). Students were required to show some work explaining how they arrived at their answer. Several mathematical approaches were possible with the two most common methods included in the rubric.

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 2.02 out of a possible 4 points. The distribution of points on this question is shown below.



Less than half of the responses to part (a) earned the point. Some failed to connect the number and height of the peaks with the type and number of electrons in the element. Others misinterpreted the x-axis as molar mass (effectively reading the photoelectron spectrum as though it were a mass spectrum) or atomic number. Student responses included most of the elements on the periodic table. Students often added helpful labels like “ $1s^2$, $2s^2$, $2p^3$ ” above the first, second, and third peaks respectively, and then used this electron configuration to identify the element.

In part (b), more than half of the student responses earned the point. Most students correctly used a mathematical routine to calculate the value of the rate constant. A significant number of students converted the half-life of 10 min to 600 s before applying the mathematical formula; this step was acceptable but unnecessary. The second point assigned to part (b), for the inclusion of correct units, was the least-earned point in Question 7. Most students used an incorrect unit (often minutes, rather than inverse minutes) or did not include a unit at all.

Part (c) was the most frequently-earned point on this question. Most students showed how they arrived at their answer by successively halving the number of atoms as a way of determining the number of half-lives that had elapsed. Some students showed this method in the form of a half-life table. A significant number of students solved for the timer variable in the integrated rate law for a first-order process. These students followed the mathematically valid approach of substituting the number of atoms in place of molarity. Students were required to include some type of supporting work to earn the point for this part.

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>
Part (a): Misinterpreting peak height: <ul style="list-style-type: none"> - Thinking the $2p$ sublevel was full, and identifying neon - Thinking the $2p$ sublevel contained only 1 electron, and identifying boron - Thinking each peak represented 1 electron, and identifying lithium Misinterpreting the x-axis as: <ul style="list-style-type: none"> - Atomic number, and identifying zirconium ($Z = 40$) - Atomic mass, and identifying calcium (40 g/mol) 	The element is nitrogen.
Part (b): Algebraic errors. Including time units (e.g., min or s) instead of inverse time units. Adding extra quantities to the inverse time units (e.g., atoms/min, mol/min, decays/min).	$k = \frac{0.693}{t_{1/2}} = \frac{0.693}{10. \text{ min}} = 0.069 \text{ min}^{-1}$

<p>Part (c):</p> <p>Miscounting number of half-lives at the beginning or end of the decay sequence.</p> <p>Miscalculating time by starting with 64 atoms at $t = 10$. minutes rather than 64 atoms at $t = 0$ minutes.</p> <p>Reducing the half-life by a factor of two for every successive half-life. Thus students claimed that it took 10 minutes for 64 atoms to decay to 32 atoms, then 5 minutes for 32 atoms to decay to 16 atoms, then 2.5 minutes for 16 atoms to decay to 8 atoms, and so forth.</p> <p>Using the second-order integrated rate law.</p>	<p>Counting number of half-lives elapsed:</p> <table border="1" style="margin-left: auto; margin-right: auto;"> <thead> <tr> <th>Number of Atoms</th> <th>Time (min)</th> </tr> </thead> <tbody> <tr> <td>64</td> <td>0</td> </tr> <tr> <td>32</td> <td>10.</td> </tr> <tr> <td>16</td> <td>20.</td> </tr> <tr> <td>8</td> <td>30.</td> </tr> <tr> <td>4</td> <td>40.</td> </tr> <tr> <td>2</td> <td>50.</td> </tr> <tr> <td>1</td> <td>60.</td> </tr> </tbody> </table> <p>Answer: 60. min or 3600 s or 1.0 hr</p>	Number of Atoms	Time (min)	64	0	32	10.	16	20.	8	30.	4	40.	2	50.	1	60.
Number of Atoms	Time (min)																
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1	60.																

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

- Compare and contrast various types of graphical, instrumental data (versus mass spectrometry versus absorption spectroscopy) to clarify what kind of information each experiment provides.
- Reinforce the importance of including units throughout a calculation. Avoid unnecessary unit conversions when a specific type of unit is not required.
- Require students to show their work, even when mental math is possible. The instructions at the beginning of the free-response section says that work must be shown to receive credit.
- Write units clearly, using standard abbreviations. Labels like “m” or “M” (which are reserved for other quantities) is a poor way to express units of minutes.

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

- Teachers will find sample student responses to exam questions on the exam information page on AP Central, along with specific commentary explaining why each point was or was not earned. Teachers can use these samples to work with students to help them become more comfortable in practicing and producing responses within the suggested response time, so that students devote an appropriate amount of time for each question.
- Teachers will find scoring guidelines explaining how the exam questions were scored on the exam information page on AP Central. Teachers can use and adapt these scoring guidelines throughout the AP year so that students become familiar with how their responses will be scored.
- Teachers can review elements of Q2 from the 2017 exam, Q2 and Q5 from the 2016 exam, and Q5 from the 2015 exam and Q7 from the 2014 exam.
- Teachers can use the guidebook *Quantitative Skills in the AP Sciences* (2018) to assist students in developing quantitative skills throughout the course.
- The AP Chemistry Online Teacher Community is active and there are many discussions concerning teaching tips, techniques, and activities that many teachers have found helpful. It is easy to sign up for and you can search topics of discussions from all previous years.
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