

## Chief Reader Report on Student Responses: 2019 AP<sup>®</sup> Chemistry Free-Response Questions

• Number of Students Scored	158,847		
• Number of Readers	367		
• Score Distribution	Exam Score	N	%At
	5	18,220	11.5
	4	26,393	16.6
	3	43,646	27.5
	2	36,537	23.0
	1	34,051	21.4
• Global Mean	2.74		

The following comments on the 2019 free-response questions for AP<sup>®</sup> Chemistry were written by the Chief Reader, Paul Bonvallet, 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.

**NOTE:** The 2019 exam is the last to use the Learning Objectives and Science Practices from the Fall 2014 AP Chemistry Course and Exam Description. Subsequent exams will be written according to those from the Fall 2019 AP Chemistry Course and Exam Description. These updated guidelines change only the organization of the content, not the content itself, and thus will not change the AP Chemistry Exam.

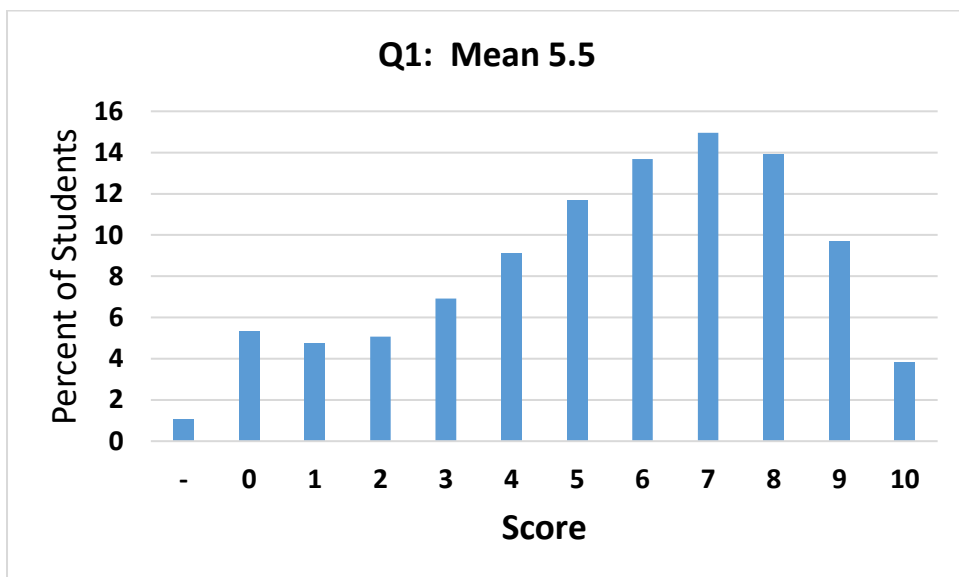
**Question #1****Task:** Structure and behavior of urea**Topics:** Lewis structure, calorimetry, thermodynamics**Max. Points:** 10**Mean Score:** 5.54**What were the responses to this question expected to demonstrate?**

Question 1 addresses multiple concepts and skills related to aqueous solutions of urea. In part (a) students are provided with a Lewis structure of urea and asked to identify the hybridization of the atomic orbitals around the carbon atom (LO 2.21; SP 1.4). Part (b) shows a particulate representation of one urea molecule with several molecules of water surrounding it. Students are asked to draw a dashed line to indicate one possible location of a hydrogen bond between a water molecule and the urea molecule (LO 2.13; SP 1.4, 6.4). Part (c) requires the calculation of the molar concentration of urea in a saturated solution (LO 3.4; SP 2.2, 5.1, 6.4). Part (d) reports that the concentration of urea in a saturated solution is higher at elevated temperature. Based on this result students are asked to predict whether the dissolution of urea is endothermic or exothermic and to explain their answer in terms of Le Chatelier's principle (LO 6.8; SP 1.4, 6.4). Part (e) shows several pieces of laboratory equipment and asks for a list of specific measurements that must be made to determine the molar heat of solution for urea (LO 5.7; SP 4.2, 5.1, 6.4).

The remainder of this question deals with the thermodynamics of the dissolution of urea. In part (f) students calculate the standard absolute entropy of aqueous urea given the standard entropy change for dissolution ( $\Delta S_{soln}^{\circ}$ ) and the standard absolute molar entropy of solid urea (LO 5.13; SP 2.2, 6.4). By extension, part (g) asks for a particle-level explanation for why  $\Delta S_{soln}^{\circ}$  is positive for the dissolution of urea in water. Finally, in part (h), students explain the contribution that  $\Delta S_{soln}^{\circ}$  makes to the overall thermodynamic favorability of the dissolution process.

**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 5.5 out of a possible 10 points, with a standard deviation of 2.7 points. The distribution of points on this question is shown below.



Nearly every student attempted to answer at least one part of this question. Parts (a) through (c) were accessible for most students, although in part (b) the dashed line sometimes indicated the association of incorrect atoms (e.g., the oxygen atom in water and the nitrogen atom in urea). Computational errors in part (c) included flawed mathematical operations, severe or premature rounding in intermediate work, or incorrect conversion between milliliters and liters.

In part (d), most students correctly attributed the difference in solubility to a change in temperature but varied in their ability to connect that observation to the endothermicity of the dissolution and/or use Le Chatelier's principle

convincingly. Students generally recognized part (e) as a calorimetry experiment, but either gave too little detail (e.g., only “find  $\Delta T$ ”) or far too much detail (providing a stepwise laboratory procedure for the entire experiment, sometimes omitting any mention of the measurements that were necessary).

The responses to part (f) were often correct, but most students struggled in part (g) to describe entropy change in terms of particle-level behavior. Words like “disorder” and “chaos” were frequently used as surrogates for the dispersion (number of possible arrangements) of the energy or physical location of the particles. While students were allowed to use a simplified definition of entropy commensurate with the AP Chemistry curriculum, short or overly-vague answers did not receive credit because they were not supported by chemical reasoning at the particle level.

Many students correctly stated in part (h) that a positive  $\Delta S^\circ_{\text{soln}}$  contributes to the thermodynamic favorability of dissolution. However, some answers failed to connect  $\Delta S^\circ$  to the broader context of  $\Delta G^\circ$ . Some claimed that  $\Delta S^\circ$  is the only determinant of thermodynamic favorability, or that any process with a positive  $\Delta S^\circ$  will always be thermodynamically favorable.

**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): Incorrect hybridization (often $sp^3$ , $sp^4$ , $sp^3d^2$ ) Irrelevant information, such as electron configuration, instead of hybridization	$sp^2$
Part (b): Improper identification of the hydrogen bond interaction, such as intermolecular interactions between O---N or H--H	A dashed line should connect a hydrogen atom in water to a nitrogen or oxygen atom in urea, or an oxygen atom in water to a hydrogen atom in urea
Part (c): Using an incorrect molar mass Dividing molar mass by the mass of the urea sample, giving $60.06 \text{ g/mol} \div 5.39 \text{ g} = 11.14 \text{ mol}^{-1}$ Incorrect rounding, converting 0.0897 mol to 0.08 mol Incorrect conversion between mL and L, such as $5.00 \text{ mL} = 0.050 \text{ L}$ or $5.00 \text{ mL} = 5.00 \text{ L}$ Multiplying the mass of the urea sample by the volume of the solution Incorrectly using the ideal gas equation	$5.39 \text{ g H}_2\text{NCONH}_2 \times \frac{1 \text{ mol}}{60.06 \text{ g}} = 0.0897 \text{ mol}$ $\frac{0.0897 \text{ mol}}{0.00500 \text{ L}} = 17.9 \text{ M}$
Part (d): Misinterpreting the experimental result, claiming either an equilibrium shift towards reactants at elevated	The increased solubility at the higher temperature implies that the dissolution of urea is endothermic. If a saturated solution of urea is heated, then the equilibrium

temperature or concluding that the dissolution is exothermic	system is stressed. The stress is counteracted by the endothermic dissolution of more urea.
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<i>Common Misconceptions/Knowledge Gaps</i>	<i>Responses that Demonstrate Understanding</i>
<p>Part (e):</p> <p>Detailing an entire procedure for the calorimetry experiment, rather than listing measurements</p> <p>Taking the initial temperature measurement after the urea has been combined with water, rather than before</p> <p>Omitting a key measurement (most frequently the mass of the water)</p> <p>Using laboratory equipment to record derived quantities rather than direct measurements (e.g., using a thermometer to measure <math>q</math> or <math>\Delta T</math>)</p> <p>Conflating heat and temperature, as in “measure the heat”</p>	<p>mass of urea, mass of water, initial temperature of water, final temperature of solution</p>
<p>Part (f):</p> <p>Incorrect mathematical operations or algebraic manipulations.</p>	$\Delta S_{soln}^{\circ} = S^{\circ}(\text{H}_2\text{NCONH}_2(aq)) - S^{\circ}(\text{H}_2\text{NCONH}_2(s))$ $70.1 \text{ J}/(\text{mol}\cdot\text{K}) = S^{\circ}(\text{H}_2\text{NCONH}_2(aq)) - 104.6 \text{ J}/(\text{mol}\cdot\text{K})$ $S^{\circ}(\text{H}_2\text{NCONH}_2(aq)) = 174.7 \text{ J}/(\text{mol}\cdot\text{K})$
<p>Part (g):</p> <p>Failure to use particle-level reasoning</p> <p>Restating the definition of entropy, rather than using it to provide evidence</p> <p>Describing the system only in terms of “disorder” or “chaos” (preferred terms: arrangements or dispersion of matter / energy) in the absence of chemical reasoning</p> <p>Interpreting <math>\Delta S^{\circ}</math> as a difference in two energies</p>	<p>Urea molecules in solution have a greater number of possible arrangements than in solid urea. This increased number of arrangements corresponds to a positive <math>\Delta S_{soln}^{\circ}</math>.</p>
<p>Part (h):</p> <p>Failing to mention <math>\Delta G^{\circ}</math> and/or <math>\Delta H^{\circ}</math>, or stating that <math>\Delta S^{\circ}</math> is the only determinant of thermodynamic favorability</p> <p>Stating that all processes with <math>\Delta S^{\circ} &gt; 0</math> will always be thermodynamically favorable</p>	<p>Thermodynamic favorability for a process at standard conditions is determined by the sign of <math>\Delta G^{\circ}</math>, with <math>\Delta G^{\circ} = \Delta H^{\circ} - T\Delta S^{\circ}</math>. Since <math>\Delta S^{\circ}</math> is positive, the <math>T\Delta S^{\circ}</math> term makes the value of <math>\Delta G^{\circ}</math> smaller and thus makes the dissolution more thermodynamically favorable.</p>

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

1. Be sure that students understand the definition of hybridization (as opposed to electron configuration) and methods used to determine which hybrid atomic orbitals are involved in bonding.

2. Encourage students to use correct and complete dimensional analysis, with units, in all calculations to avoid simple mistakes (like  $5.00 \text{ mL} = 0.050 \text{ L}$ , or expressing molarity in units of  $\text{mol}^{-1}$ ).
3. Clarify the difference between a measurement (like mass or temperature) vs. a derived quantity ( $\Delta T$ ,  $q$ , or specific heat).
4. Help students to understand that the  $m$  term in  $q=mc\Delta T$  represents the mass of the entire solution, rather than the mass of the solvent or solute alone.
5. Resist the shortcut of equating entropy with “disorder.” An increase in entropy is an increase in the dispersion of energy states within a system. Thus, increased disorder is the effect, not the cause, of an increase in entropy.
6. Emphasize that  $\Delta G^\circ$  determines the thermodynamic favorability of a process, not just  $\Delta S^\circ$  (or  $\Delta H^\circ$ ) individually.
7. Ask students to define chemical terms with precise, correct language. Some common errors in terminology included hydrogen bonding vs. covalent bonding, formula variables vs. experimental measurements, or heat vs. temperature.

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

- Several years’ worth of AP Chemistry free response questions and the associated scoring guidelines are archived on the AP Central website (<https://apcentral.collegeboard.org/courses/ap-chemistry/>). This site also contains sample student responses to exam questions along with specific commentary explaining why each point was or was not earned.
- Teachers can use these online samples and scoring guidelines throughout the year to help students become comfortable in practicing and producing responses within the suggested response time. They can also learn more about the procedures by which their responses will be scored.
- In AP Classroom, teachers will find a rich, new collection of resources for the 2019 school year that includes newly created formative and summative assessment items for every unit of the course and that represents each of the types of questions on the AP Exam. This includes practice FRQs for teachers to use as formative assessment pieces beginning with scaffolded questions that represent what students are ready for at the beginning of the school year and an increased challenge as teacher’s progress through the course.
- The guidebook *Quantitative Skills in the AP Sciences* (2018) can assist teachers in strengthening their students’ quantitative skills throughout the course.
- The AP Chemistry Online Teacher Community (<https://apcommunity.collegeboard.org/web/apchem>) is very active, and there are many discussions concerning teaching tips, techniques, and activities that many teachers have found helpful. It is easy to join, and you can search topics and discussions from previous years.
- Newer teachers (and career changers) should consider signing up for an AP Summer Institute (APSI). An APSI is a great way to gain in-depth teaching knowledge on the AP Chemistry curriculum and exam and is also an opportunity to network with colleagues from around the country.

**Question #2****Task:** Analysis of various halogen compounds**Max. Points:** 10**Topics:** Electrochemistry, intermolecular forces, equilibrium**Mean Score:** 4.72***What were the responses to this question expected to demonstrate?***

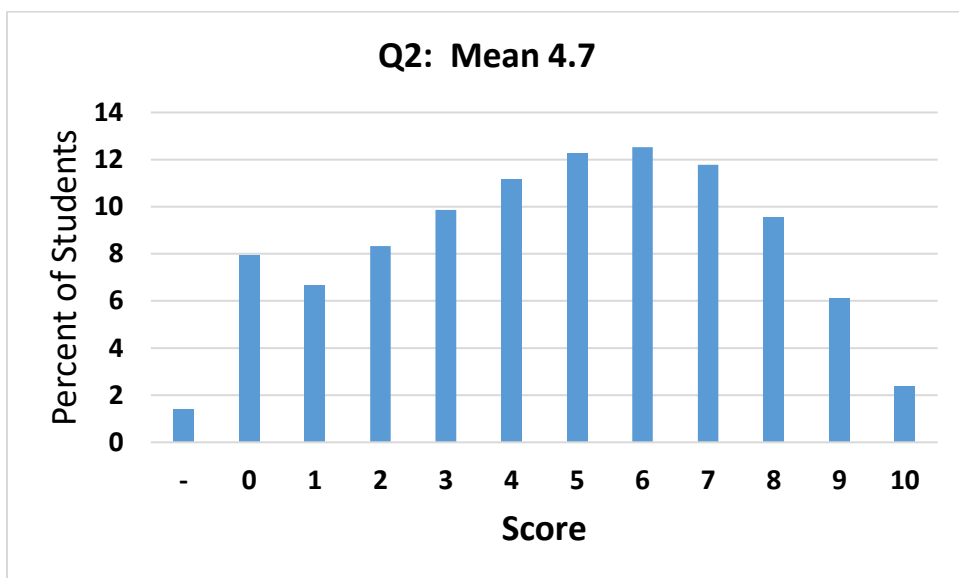
Question 2 incorporates a wide range of concepts (atomic structure, intermolecular forces, equilibrium) within the context of elemental halogens and the interhalogen compound BrCl. This question also highlights electrochemistry, the ideal gas law, and bond dissociation enthalpy.

In part (a) students are asked which among four elemental halogen compounds has the longest bond length. They must make a correct selection and justify their choice in terms of atomic structure (LO 2.21; SP 1.4). Part (b) provides a table of half-reactions, with standard potentials, for the reduction of various elemental halogen compounds. The student must use this information to write a balanced chemical equation for the thermodynamically favorable preparation of Br<sub>2</sub> and justify the favorability by calculating  $E^\circ$  for the process (LO 3.12; SP 2.2, 6.4). The intent is for students to recognize that only one of the reagents can oxidize Br<sup>-</sup> to Br<sub>2</sub> in a thermodynamically favorable reaction (i.e., positive value of  $E^\circ$ ).

In part (c) students are asked to explain the difference between the boiling points of Br<sub>2</sub> and BrCl. They need to identify the intermolecular forces present between molecules of each substance and use that information to explain why Br<sub>2</sub> has a higher boiling point than BrCl (LO 5.9; SP 6.4). Part (d) requires a calculation of the initial pressure of BrCl(g) reactant in a rigid container prior to its decomposition into Br<sub>2</sub>(g) and Cl<sub>2</sub>(g). Students should use the ideal gas law and report the pressure in units that are consistent with the version of the gas constant  $R$  that they use (LO 2.6; SP 2.2). After equilibrium is established, students must write the expression for the equilibrium constant in part (e) and then determine the value of that constant in part (f) (LO 6.5; SP 2.2). Either a  $K_c$  or  $K_p$  expression is appropriate in this case. Part (g) gives a partial table of bond dissociation enthalpies and asks the student, given  $\Delta H^\circ$  for the reaction, to calculate the bond energy of the Br–Cl bond (LO 5.8; SP 2.3, 7.1, 7.2). Students must use Hess's law to find this missing value.

***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 4.7 out of a possible 10 points, with a standard deviation of 2.8 points. The distribution of points on this question is shown below.



Overall, students did well in part (a) recognizing that  $I_2$  has the longest halogen-halogen bond due to iodine having the largest atomic radius among the four halogens. Some responses did not receive credit because they merely defined what bond length is, rather than using principles of atomic structure to explain the differences among the halogens. In part (b), many students wrote good balanced redox equations (either molecular or net ionic) and successfully calculated the standard cell potential for this process. Sometimes students provided an incorrect or unbalanced equation, but they could still earn the second point if the reaction gave  $Br_2$  as a product and had a value of  $E^\circ$  that was consistent with that reaction.

Students struggled in part (c), often earning 1 or zero points out of the possible 2. Many responses incorrectly stated that  $BrCl$  has only London dispersion forces or discussed intramolecular forces instead of intermolecular forces. Students often earned the second point on part (c) for attributing the higher boiling point of  $Br_2$  to the totality of its intermolecular forces being stronger than those in  $BrCl$ .

Students answered part (d) correctly most of the time. They could report the pressure of  $BrCl$  in any valid unit, so long as it was consistent with the version of the gas constant  $R$  that they used. Correspondingly, units were required in order to receive credit. Students were also largely successful in answering part (e). Since the prompt asked for a generic  $K_{eq}$ , students could write either a  $K_p$  or  $K_c$  expression. Common errors included omitting the exponent in the  $BrCl$  term or incorrect/ambiguous notation that made it unclear whether they were expressing the concentration or partial pressure of each species. A majority of students earned only 1 point out of 2 for part (f), most often by ignoring the reaction stoichiometry when calculating the equilibrium constant. Even if their partial pressures (or concentrations) at equilibrium were incorrect, students could still earn the second point if they substituted these values correctly in their  $K_{eq}$  expression. Another common error was failing to square the partial pressure (or concentration) of  $BrCl$  in the  $K_{eq}$  expression. In keeping with our practice of penalizing only once for a single mistake, this error was forgiven if the  $K_{eq}$  expression in part (e) was also missing the exponent for  $BrCl$ . However, a substantial number of students had the  $BrCl$  term correctly squared in their answers to part (e) but then not squared in part (f). This set of students did not earn the second point due to the inconsistent form of their equilibrium expression.

Most students did not earn credit for part (g). Some responses neglected the reaction stoichiometry or failed to include  $\Delta H^\circ$  in the calculation. Others interpreted the bond energy as a heat of formation or used the reverse mathematical relationship

$$\Delta H^\circ = \sum (\text{bond energies})_{\text{formed}} - \sum (\text{bond energies})_{\text{broken}}$$

**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>Only stating the definition of bond length, rather than explaining the trend in bond length</p> <p>Using vague language that made it unclear whether the student was describing the size of the I<sub>2</sub> molecule or an individual iodine atom</p>	<p>I<sub>2</sub> has the longest bond length because the radius of the I atom is greater than the radii of the other halogen atoms. Thus, the distance between the nuclei of atoms in I<sub>2</sub> is greater than it is in smaller halogens.</p>
<p>Part (b):</p> <p>Adding together two oxidation half-reactions or two reduction half-reactions</p> <p>Failing to recognize that <math>E^\circ</math> must be positive in a thermodynamically favorable reaction</p>	$2 \text{Br}^- \rightarrow \text{Br}_2 + 2 e^- \quad (\text{oxidation})$ $\text{Cl}_2 + 2 e^- \rightarrow 2 \text{Cl}^- \quad (\text{reduction})$ <hr/> $2 \text{Br}^- + \text{Cl}_2 \rightarrow \text{Br}_2 + 2 \text{Cl}^-$ $E^\circ = E^\circ (\text{reduced species}) - E^\circ (\text{oxidized species})$ $= 1.36 \text{ V} - 1.07 \text{ V} = +0.29 \text{ V}$ <p>Because <math>E^\circ</math> for the reaction has a positive value, the reaction is thermodynamically favorable.</p>
<p>Part (c):</p> <p>Confusing intermolecular forces with intramolecular forces (e.g., explaining boiling point trends in terms of attraction between an electron and the nucleus)</p> <p>Failing to recognize that London dispersion forces can be stronger than dipole-dipole interaction</p> <p>Missing the presence of dipole-dipole interactions among molecules of BrCl</p>	<p>The only intermolecular attractions in Br<sub>2</sub>(l) are London forces, while those in BrCl(l) include both London forces and dipole-dipole forces. However, due to the greater polarizability of the electron cloud of Br<sub>2</sub> compared to that of BrCl, the London forces in Br<sub>2</sub>(l) are stronger than the combined intermolecular forces in BrCl(l). Thus the boiling point of Br<sub>2</sub>(l) is greater than that of BrCl(l).</p>
<p>Part (d):</p> <p>Reporting a pressure with no units or a unit inconsistent with the gas constant (<math>R</math>) used in the calculation</p> <p>Assuming 0.200 mol BrCl due to the stoichiometric coefficient of 2 in the balanced chemical equation</p>	$P = \frac{nRT}{V} = \frac{(0.100 \text{ mol})(0.08206 \text{ L atm mol}^{-1} \text{ K}^{-1})(298 \text{ K})}{2.00 \text{ L}} = 1.22 \text{ atm}$ <p>Other acceptable answers include:</p> <p><math>P = 124 \text{ J/L}</math> or <math>124 \text{ kPa}</math> (from <math>R = 8.31 \text{ J mol}^{-1} \text{ K}^{-1}</math>)</p> <p><math>P = 929 \text{ torr}</math> (from <math>R = 62.36 \text{ L torr mol}^{-1} \text{ K}^{-1}</math>)</p>
<p>Part (e):</p> <p>Writing chemical species that are not part of the reaction, such as Br or Cl</p> <p>Expressing concentration with parentheses rather than square brackets, or overlooking brackets altogether</p> <p>Omitting “<math>P</math>” to denote partial pressure</p> <p>Failing to account for reaction stoichiometry</p>	$K_{eq} = \frac{[\text{Br}_2][\text{Cl}_2]}{[\text{BrCl}]^2} \quad \text{or} \quad K_{eq} = \frac{P_{\text{Br}_2} P_{\text{Cl}_2}}{(P_{\text{BrCl}})^2}$



(neglecting to square the partial pressure or concentration of BrCl)													
<p>Part (f):</p> <p>Ignoring the reaction stoichiometry when calculating the change in partial pressure (or concentration) of species as equilibrium is reached</p> <p>Interpreting “42 percent of the original BrCl sample has decomposed” to mean that at equilibrium, 42 percent of the BrCl sample remains</p>	$2 \text{BrCl}(g) \rightleftharpoons \text{Br}_2(g) + \text{Cl}_2(g)$ <table border="1"> <tr> <td>I</td> <td>1.22</td> <td>0</td> <td>0</td> </tr> <tr> <td>C</td> <td>-2x</td> <td>+x</td> <td>+x</td> </tr> <tr> <td>E</td> <td>0.71</td> <td>0.26</td> <td>0.26</td> </tr> </table> <p><math>P_{\text{BrCl decomposed}} = (0.42)(1.22 \text{ atm}) = 0.51 \text{ atm}</math></p> <p><math>2x = 0.51 \text{ atm} \Rightarrow x = 0.26 \text{ atm}</math></p> <p><math>K_{eq} = \frac{(0.26)(0.26)}{(0.71)^2} = 0.13</math></p> <p><u>Note:</u> The solution above is in terms of pressures. Solutions in terms of molar concentrations also earn full credit.</p>	I	1.22	0	0	C	-2x	+x	+x	E	0.71	0.26	0.26
I	1.22	0	0										
C	-2x	+x	+x										
E	0.71	0.26	0.26										
<p>Part (g):</p> <p>Using the backwards relationship</p> <p><math>\Delta H^\circ = \sum (\text{bond energies})_{\text{formed}} - \sum (\text{bond energies})_{\text{broken}}</math></p> <p>Omitting <math>\Delta H^\circ</math> from the calculation</p> <p>Neglecting the reaction stoichiometry</p> <p>Interpreting “bond energy” as a heat of formation</p>	<p><math>\Delta H^\circ = \sum (\text{bond energies})_{\text{broken}} - \sum (\text{bond energies})_{\text{formed}}</math></p> <p><math>1.6 \text{ kJ/mol} = 2(\text{Br-Cl bond energy}) - (193 \text{ kJ/mol} + 243 \text{ kJ/mol})</math></p> <p><math>(436 + 1.6) \text{ kJ/mol} = 2(\text{Br-Cl bond energy})</math></p> <p>Br-Cl bond energy = 219 kJ/mol</p>												

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

1. Require students to include units with all intermediate mathematical work and every answer. This practice helps to avoid simple mistakes, such as reporting a unit for gas pressure that is inconsistent with the gas constant  $R$ .
2. Practice writing full chemical equations from a pair of redox half-reactions.
3. Practice identifying intermolecular forces in various compounds and explain their impact on physical properties.
4. Ask students to solve  $\Delta H^\circ$  problems using both bond energies and heats of formation so that they understand the difference between the two terms.
5. Require students to use clear and correct language in their explanations. Some common errors on this question include:
  - a. using molar mass as a proxy for atomic radius
  - b. confusing intermolecular forces with intramolecular forces
  - c. implicitly or explicitly referring to intermolecular forces as “bonds”
  - d. confusing bond dissociation enthalpy with heat of formation

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

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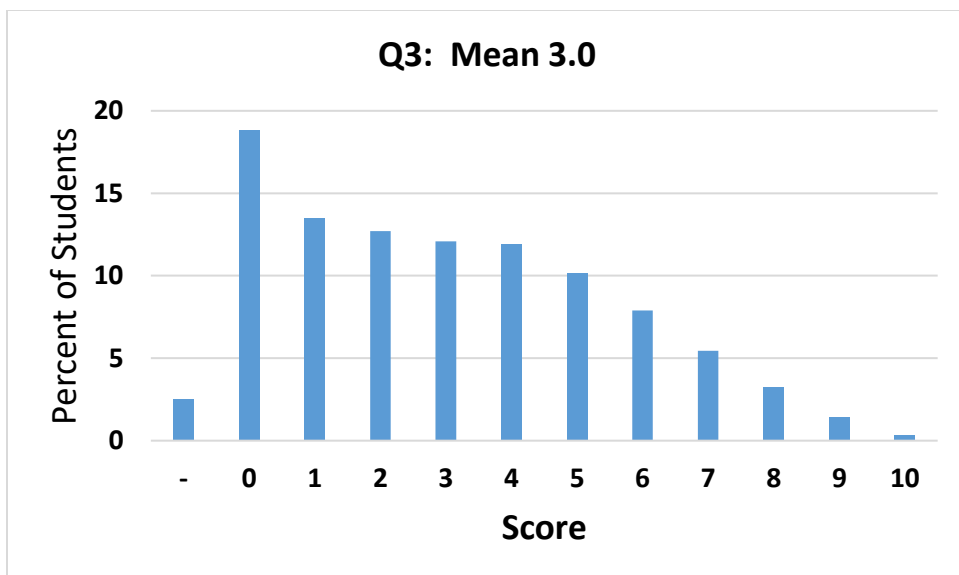
**Question #3****Task:** Analysis of sodium carbonate solutions**Max. Points:** 10**Topics:** Net ionic equations, stoichiometry, lab error analysis, acid-base equilibria**Mean Score:** 3.01***What were the responses to this question expected to demonstrate?***

The broad goal in this question is for students to determine the concentration of  $\text{Na}_2\text{CO}_3$  in an aqueous solution of unknown concentration using two different methods: gravimetric analysis and pH determination. Part (a) asks for the balanced net-ionic equation for the precipitation of  $\text{CaCO}_3$  from an aqueous solution of  $\text{Na}_2\text{CO}_3$  and  $\text{Ca}(\text{NO}_3)_2$  (LO 3.2; SP 1.5, 7.1). Part (b) focuses on the conceptual understanding of the experiment by providing an incomplete particulate representation of the reaction vessel and having the student draw the missing species (LO 3.4; SP 2.2, 5.1, 6.4). The next three parts deal with the mechanics of the precipitation experiment. Part (c) requires students to interpret a data table to calculate, from the mass of  $\text{CaCO}_3$  precipitate, the number of moles of  $\text{Na}_2\text{CO}_3$  that were present in the original aqueous solution (LO 3.4; SP 2.2, 5.1, 6.4). Part (d) is an error analysis question where students predict and then explain the effect that an incompletely dried precipitate would have on the calculated molarity of the  $\text{Na}_2\text{CO}_3$  solution (LO 1.19; SP 4.2, 5.1, 6.4). Part (e) asks students to predict and explain whether the filtrate would be electrically conductive, requiring them to recognize the presence of ions and connect that characteristic to conductivity (LO 2.10; SP 4.2, 5.1, 6.4).

The remainder of the question deals with a second method for determining the concentration of  $\text{Na}_2\text{CO}_3$ . In part (f) students identify a laboratory method other than titration for determining  $[\text{OH}^-]$  in the solution. The “not titration” constraint examines the breadth of students’ laboratory knowledge while avoiding the complexities of titration in relating the equilibrium concentration of  $\text{OH}^-$  to the concentration of a polybasic ion like  $\text{CO}_3^{2-}$  in the next part of the question. The second section of part (f) asks for a description of the mathematical routine that would lead from the measured value of  $[\text{OH}^-]$  to the initial concentration of  $\text{Na}_2\text{CO}_3$  in the original solution. This question bypasses algorithmic problem-solving to assess a conceptual understanding of the experimental method. Both sections of part (f) address LO 6.16; SP 2.2 and 6.4. In part (g) students are asked to compare the relative concentrations of  $\text{HCO}_3^-$  vs.  $\text{CO}_3^{2-}$  in the original  $\text{Na}_2\text{CO}_3$  solution and justify their answer (LO 6.17; SP 6.4). Part (h) presents a scenario in which students need to prepare a buffer solution with a pH of 6 and asks students to explain whether the  $\text{Na}_2\text{CO}_3$  solution could be used to prepare this buffer (LO 6.18; SP 2.3, 4.2, 6.4). This question assesses students’ ability to evaluate the relative concentrations of a weak acid/conjugate base pair in relation to the pH of the 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 3 was 3.0 out of a possible 10 points, with a standard deviation of 2.5 points. The distribution of points on this question is shown below.



Although Question 3 had the highest proportion of students who left the page blank (2.4%), most students earned a few points. These points were usually earned in the first section of this question in parts (a) through (e). Many students earned the point in part (a), although some responses included spectator ions or used incorrect (or missing) electronic charge on the ions. Part (b) was generally a low-scoring question. At least one  $\text{Ca}^{2+}$  ion was necessary for consistency with the experimental conditions of excess  $\text{Ca}(\text{NO}_3)_2$ , but most students drew only  $\text{Na}^+$  ions. Credit was awarded for multiple  $\text{Ca}^{2+}$  ions if they were accompanied by an appropriate number of nitrate counterions to achieve an electronically neutral solution. Most answers to part (c) were correct. Common incorrect answers arose from students using a reaction stoichiometry other than 1:1 or calculating a concentration (molarity) and then explicitly calling it “number of moles.” Students were likewise strong on part (d), with most recognizing that the inclusion of water in the incompletely-dried precipitate would artificially increase the calculated concentration of  $\text{Na}_2\text{CO}_3$  in the original solution. Similarly, most students in part (e) recognized that the filtrate would contain ions ( $\text{Na}^+$ ,  $\text{Ca}^{2+}$ , and  $\text{NO}_3^-$ ) and thus conduct electricity. Occasionally students referred incorrectly to the electrical conductivity of the precipitate or interpreted the presence of metal ions to mean that the filtrate had metallic character.

The latter section of this question, parts (f) through (h), was much more challenging for students. Many responses to part (f)(i) simply said “measure the pH” without mentioning an experimental method, while others suggested unsuitable methods such as photoelectron spectroscopy or distillation. Students suggesting a single acid-base indicator (e.g., litmus paper or phenolphthalein) did not receive credit because these methods only report whether the pH of a solution is above or below a certain threshold. However, those who proposed using a universal indicator or multiple indicators to bracket the pH range did earn the point. It was very common in part (f)(ii) for students to confuse the *initial* concentration of  $\text{Na}_2\text{CO}_3$  with the *equilibrium* concentration, thus describing the ICE table effectively but failing to perform the necessary addition at the end. Others had difficulty describing the basic mathematical routine, most often by omitting or incorrectly constructing the ICE table. In part (g), several students interpreted the negative exponent of  $K_b$  to mean that the mathematical value of  $K_b$  was less than zero. Others attempted to use reaction stoichiometry to answer the question. In part (h), students had difficulty relating the value of  $K_b$  to the  $\text{p}K_a$  and comparing it to the desired pH. Some students simply indicated that  $\text{Na}_2\text{CO}_3$  is a basic salt and therefore can never be present in an acidic solution. Responses were required to reference some component of buffer chemistry (e.g.,  $\text{p}K_b$  or  $\text{p}K_a$ ) to earn credit.

**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>Failure to balance the equation with respect to mass and/or charge</p> <p>Including spectator ions</p> <p>Incorrect electronic charge on one or more ions</p> <p>Omitting electronic charge from one or more ions</p>	$\text{Ca}^{2+}(\text{aq}) + \text{CO}_3^{2-}(\text{aq}) \rightarrow \text{CaCO}_3(\text{s})$
<p>Part (b):</p> <p>Adding two <math>\text{Na}^+</math> ions instead of one <math>\text{Ca}^{2+}</math> ion, neglecting the experimental conditions of <math>\text{Ca}(\text{NO}_3)_2</math> being in excess</p> <p>Drawing multiple <math>\text{Ca}^{2+}</math> ions with too few <math>\text{NO}_3^-</math> counterions to balance electronic charge</p> <p>Including <math>\text{CO}_3^{2-}</math> ions in the diagram</p>	<p>The drawing shows one <math>\text{Ca}^{2+}</math> ion.</p>
<p>Part (c):</p> <p>Calculating the molarity of <math>\text{Na}_2\text{CO}_3</math> and labeling it as “number of moles”</p> <p>Using the dilution equation <math>M_1V_1 = M_2V_2</math></p> <p>Assuming a 2:1 molar relationship between <math>\text{Na}_2\text{CO}_3</math> and <math>\text{CaCO}_3</math>, instead of 1:1</p> <p>Converting solution volume into number of moles with the standard molar volume of a gas (22.4 L/mol)</p> <p>Multiplying the volume of the original <math>\text{Na}_2\text{CO}_3</math> solution by the molarity of the excess <math>\text{Ca}(\text{NO}_3)_2</math></p>	$0.93 \text{ g CaCO}_3 \times \frac{1 \text{ mol CaCO}_3}{100.1 \text{ g}} = 0.0093 \text{ mol CaCO}_3$ $0.0093 \text{ mol CaCO}_3 \times \frac{1 \text{ mol Na}_2\text{CO}_3}{1 \text{ mol CaCO}_3} = 0.0093 \text{ mol Na}_2\text{CO}_3$
<p>Part (d):</p> <p>Claiming that the error would have no effect on the calculated molarity of <math>\text{Na}_2\text{CO}_3</math>, for various incorrect reasons</p> <p>Indicating that the presence of water in the precipitate adds volume to the precipitate and therefore lowers the calculated molarity of <math>\text{Na}_2\text{CO}_3</math> (since the denominator in the mathematical expression for concentration becomes larger)</p> <p>Ambiguous or incorrect wording that confuses calculated concentration of <math>\text{Na}_2\text{CO}_3</math> with actual concentration</p>	<p>Disagree. The presence of water in the solid will cause the measured mass of the precipitate to be greater than the actual mass of <math>\text{CaCO}_3</math>. As a result, the calculated number of moles of <math>\text{CaCO}_3</math> and moles of <math>\text{Na}_2\text{CO}_3</math> will be greater than the actual moles present. Therefore, the calculated concentration of <math>\text{Na}_2\text{CO}_3(\text{aq})</math> will be too high.</p>

<p>Part (e):</p> <p>Discussing the conductivity of the precipitate instead of the solution</p> <p>Using the presence of metal ions to impart metallic character to the filtrate</p> <p>Predicting no conductivity due to the overall electrical neutrality of the solution</p> <p>Omitting any reference to ions (e.g., the solution is conductive because water is a good conductor)</p> <p>Equating ions dissolved in a liquid to mean the same as an ionic compound in the liquid state</p> <p>Implying that solutions of ionic compounds contain free electrons that move through the liquid</p>	<p>The liquid conducts electricity because ions (<math>\text{Na}^+(aq)</math>, <math>\text{Ca}^{2+}(aq)</math>, and <math>\text{NO}_3^-(aq)</math>) are present in the solution.</p>																																
<p>Part (f)(i):</p> <p>Failing to mention an experimental method</p> <p>Suggesting unsuitable experimental methods (e.g., chromatography, gravimetric analysis, photoelectron spectroscopy, spectrophotometry, mass spectrometry, or distillation)</p> <p>Using litmus paper or a <i>single</i> indicator</p>	<p>Determine the pH of the solution using a pH meter.</p>																																
<p>Part (f)(ii):</p> <p>Missing or unsuitable explanation of how to determine <math>[\text{OH}^-]</math> from pH</p> <p>Solving for the <i>equilibrium</i> concentration of <math>\text{CO}_3^{2-}</math> rather than the <i>initial</i> concentration</p> <p>Incorrect, missing, or ambiguous details in describing the computational routine (e.g., saying only “make an ICE table” or “use <math>K_b</math>”)</p>	<p>First determine <math>[\text{OH}^-]</math> using <math>\text{pOH} = 14 - \text{pH}</math>, then <math>[\text{OH}^-] = 10^{-\text{pOH}}</math>.</p> <p>Then use the <math>K_b</math> expression and an ICE table (see example below) to determine <math>[\text{CO}_3^{2-}]</math> and <math>[\text{HCO}_3^-]</math> at equilibrium. The initial concentration of <math>\text{CO}_3^{2-}</math>, <math>c_i</math>, is equal to the sum of the equilibrium concentrations of <math>\text{CO}_3^{2-}</math> and <math>\text{HCO}_3^-</math>.</p> <table border="1" data-bbox="792 1325 1495 1539"> <thead> <tr> <th></th> <th><math>\text{CO}_3^{2-}(aq)</math></th> <th><math>+</math></th> <th><math>\text{H}_2\text{O}(l)</math></th> <th><math>\rightleftharpoons</math></th> <th><math>\text{HCO}_3^-(aq)</math></th> <th><math>+</math></th> <th><math>\text{OH}^-(aq)</math></th> </tr> </thead> <tbody> <tr> <td>I</td> <td><math>c_i</math></td> <td></td> <td>---</td> <td></td> <td>0</td> <td></td> <td>0</td> </tr> <tr> <td>C</td> <td><math>-x</math></td> <td></td> <td>---</td> <td></td> <td><math>+x</math></td> <td></td> <td><math>+x</math></td> </tr> <tr> <td>E</td> <td><math>c_i - x</math></td> <td></td> <td>---</td> <td></td> <td><math>x</math></td> <td></td> <td><math>x</math></td> </tr> </tbody> </table> $K_b = \frac{(x)(x)}{c_i - x} \Rightarrow c_i = \frac{(x)(x)}{K_b} + x$		$\text{CO}_3^{2-}(aq)$	$+$	$\text{H}_2\text{O}(l)$	$\rightleftharpoons$	$\text{HCO}_3^-(aq)$	$+$	$\text{OH}^-(aq)$	I	$c_i$		---		0		0	C	$-x$		---		$+x$		$+x$	E	$c_i - x$		---		$x$		$x$
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E	$c_i - x$		---		$x$		$x$																										
<p>Part (g):</p> <p>Stating that <math>[\text{HCO}_3^-] &lt; [\text{CO}_3^{2-}]</math> because <math>K_b</math> is a negative number</p> <p>Predicting that <math>[\text{HCO}_3^-] = [\text{CO}_3^{2-}]</math> because the system is at equilibrium, or because the stoichiometric coefficients of reactant and product in the balanced</p>	<p>Less than. The small value of <math>K_b</math>, <math>2.1 \times 10^{-4}</math>, indicates that the reactants are favored.</p>																																

<p>chemical equation are 1:1</p> <p>Indicating that <math>[\text{HCO}_3^-] &gt; [\text{CO}_3^{2-}]</math> because:  <math>\text{HCO}_3^-</math> is a weak acid, or  the <math>\text{CO}_3^{2-}</math> undergoes a complete reaction, or  the molar mass of <math>\text{HCO}_3^-</math> is greater than that of <math>\text{CO}_3^{2-}</math></p>	
<p>Part (h):</p> <p>Mentioning only <math>\text{Na}_2\text{CO}_3</math> and neglecting any other component of the buffer (i.e., <math>\text{HCO}_3^-</math>)</p> <p>Comparing <math>\text{p}K_b</math> (instead of <math>\text{p}K_a</math>) to pH</p> <p>Treating <math>\text{p}K_a</math> and pH interchangeably (i.e., <math>\text{p}K_a = \text{pH} = 10.32</math>).</p> <p>Claiming that <math>\text{Na}_2\text{CO}_3</math> can never make an acidic buffer because it is a basic salt (with no reference to <math>\text{p}K_b</math> or <math>\text{p}K_a</math>)</p> <p>Indicating that <math>\text{Na}_2\text{CO}_3</math> is unsuitable for a buffer because it only provides one of the two necessary components in a weak base / conjugate acid pair</p>	<p>No, the <math>\text{Na}_2\text{CO}_3</math> solution is not suitable. The <math>\text{p}K_a</math> of <math>\text{HCO}_3^-</math> is 10.32. Buffers are effective when the required pH is approximately equal to the <math>\text{p}K_a</math> of the weak acid. An acid with a <math>\text{p}K_a</math> of 10.32 is not appropriate to prepare a buffer with a pH of 6.</p>

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

1. Continue to have students practice writing net-ionic equations for reactions, emphasizing the importance of showing the correct electronic charge to differentiate neutral species from ions.
2. Ask students to identify potential sources of error in their laboratory experiments and predict (with justification) the effect that such an error will have on the outcome.
3. Review, on a continuous basis, the type of information that various instruments and laboratory techniques provide.
4. Ask students to describe their problem-solving techniques, particularly with mathematical problems, to strengthen their process-oriented skills.
5. Reinforce the key conceptual and mathematical relationships in acid-base chemistry (such as pH and pOH,  $K_a$  and  $K_b$ , use of ICE tables to determine concentration at equilibrium, and the difference between initial concentration vs. equilibrium concentration).
6. Encourage students to work carefully, double-checking for a reasonable answer and computational method. This habit helps to avoid simple mistakes like applying the standard molar volume of gases to aqueous solutions or using the terms “molarity” and “number of moles” interchangeably.

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

- Several years' worth of AP Chemistry free response questions and the associated scoring guidelines are archived on the AP Central Web site (<https://apcentral.collegeboard.org/courses/ap-chemistry/>). This site also contains sample student responses to exam questions along with specific commentary explaining why each point was or was not earned.
- Teachers can use these online samples and scoring guidelines throughout the year to help students become comfortable in practicing and producing responses within the suggested response time. They can also learn more about the procedures by which their responses will be scored.
- In AP Classroom, teachers will find a rich, new collection of resources for the 2019 school year that includes newly created formative and summative assessment items for every unit of the course and that represents each of the types of questions on the AP Exam. This includes practice FRQs for teachers to use as formative assessment pieces beginning with scaffolded questions that represent what students are ready for at the beginning of the school year and an increased challenge as teacher's progress through the course.
- The guidebook *Quantitative Skills in the AP Sciences* (2018) can assist teachers in strengthening their students' quantitative skills throughout the course.
- The AP Chemistry Online Teacher Community (<https://apcommunity.collegeboard.org/web/apchem>) is very active, and there are many discussions concerning teaching tips, techniques, and activities that many teachers have found helpful. It is easy to join, and you can search topics and discussions from previous years.
- Newer teachers (and career changers) should consider signing up for an AP Summer Institute (APSI). An APSI is a great way to gain in-depth teaching knowledge on the AP Chemistry curriculum and exam and is also an opportunity to network with colleagues from around the country.

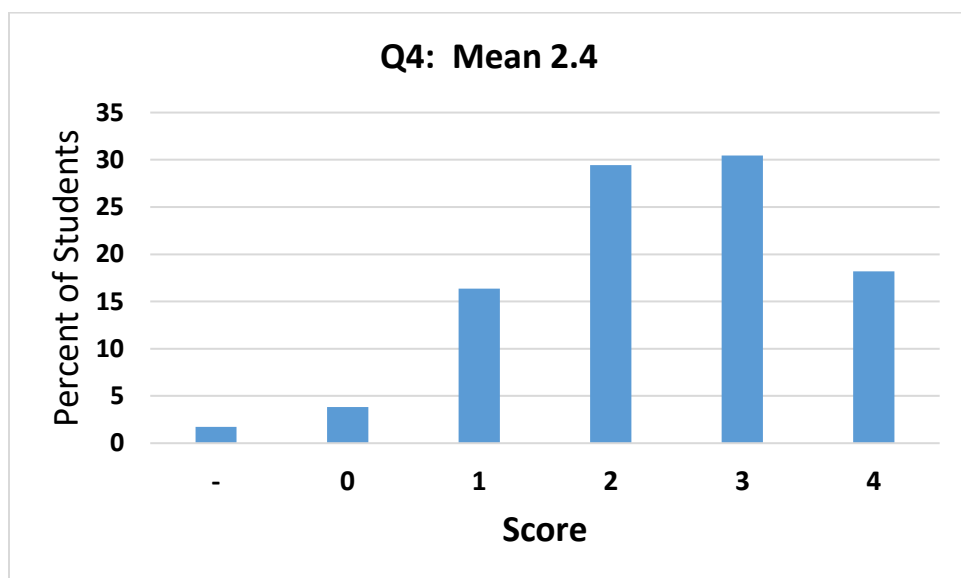


**Question #4****Task:** Relate particle-level and macroscopic phenomena in CO<sub>2</sub>**Topic:** Kinetic molecular theory, ideal and real gases**Max. Points:** 4**Mean Score:** 2.39***What were the responses to this question expected to demonstrate?***

This question assesses students' mathematical and conceptual understanding of the behavior of gaseous CO<sub>2</sub> at both the particle and macroscopic levels. In part (a) students need to associate an increase in temperature with an increase in the average kinetic energy (average velocity) of the gas particles (LO 2.4; SP 1.4, 6.4). Part (b) asks students to calculate the pressure of CO<sub>2</sub>(g) at a new elevated temperature. The most straightforward solution uses Gay-Lussac's law, since the volume of the container and the number of moles of gas particles remain constant, but another valid method uses the ideal gas equation (LO 2.6; SP 2.2). In part (c) students must explain, using principles of kinetic molecular theory, why the pressure of the gas changes as it is heated (LO 2.4; SP 1.4, 6.4). They must recognize that pressure is caused by molecules of gas colliding with the walls of the container and that at higher temperatures those collisions are more frequent and more forceful. Part (d) presents students with a scenario in which the actual pressure of CO<sub>2</sub>(g) at elevated temperature is less than that predicted by the ideal gas law (LO 2.12; SP 5.1, 6.5). Although gases may deviate from ideal behavior for a few different reasons, the presence of an attractive force between gas particles is most consistent with this experimental observation.

***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 2.4 out of a possible 4 points, with a standard deviation of 1.1 points. The distribution of points on this question is shown below.



Part (a) was the most frequently earned point in Question 4. Students used a variety of synonymous but acceptable terms to describe the greater average kinetic energy of the gas particles at higher temperature (e.g., higher velocity, faster particles, molecules moving more rapidly.) Some students highlighted the mathematical relationship between kinetic energy and velocity using  $KE = \frac{1}{2} mv^2$ , although this statement was not required for credit. Part (b) was the next most frequently earned point on this question, as most students used a correct mathematical routine to calculate the pressure. The most common solution used Gay-Lussac's law ( $P_1/T_1 = P_2/T_2$ ). Some students used the ideal gas law, showing a cancelation of the container volume and number of moles and/or carrying over information about the gas from 299 K to 425 K. This method was cumbersome but still valid. Student responses

that did not earn the point often used an incorrect formula relating temperature and pressure, or they incorrectly manipulated the correct formula.

Approximately half of the responses to part (c) earned the point. Students could mention either more frequent or more forceful collisions of CO<sub>2</sub> with the container wall. Some students incorrectly identified CO<sub>2</sub> molecules colliding with other CO<sub>2</sub> molecules as the only cause of pressure from a gas. Others were vague and simply mentioned “collisions” without specifying what was colliding with what. This type of ambiguous answer did not earn credit.

Part (d) was the least frequently earned point. Some answers cited both attractive forces and non-negligible molecular volume as causes for nonideal behavior in a gas, but failed to mention that only the former would result in a lower pressure of gas than had been predicted. On the positive side, even though this detail was not required, some students correctly identified London dispersion forces as the specific interparticle attraction that caused the deviation from ideal behavior. Many students made correct (but irrelevant) statements about the conditions under which a real gas behaves most closely to an ideal gas. For instance, some responses stated that real gases behave closest to ideal at high temperatures and low pressures. While such statements are factually correct, they do not explain the observation about CO<sub>2</sub> pressure that is described in the question. Others incorrectly claimed that ideal gases have no mass, do not collide, or are always at STP. Other responses focused instead on imaginary deficiencies in the experimental apparatus, such as a malfunctioning pressure gauge, miscalibrated thermometer, or faulty container with a leak. (When a question does require the identification of a flaw in an experimental setup, it will be worded in a direct way to guide students toward that line of thinking.)

**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>Imagining the experiment as a chemical reaction, making mention of collisions between reactant molecules and/or the amount of thermal energy available to overcome an activation barrier</p>	<p>The average speed of the molecules increases as temperature increases.</p>
<p>Part (b):</p> <p>Using an incorrect mathematical equation, usually <math>P_1 T_1 = P_2 T_2</math></p> <p>Making errors in algebra or computation</p> <p>Assuming that the vessel has a volume of 1 L and contains 1 mol of CO<sub>2</sub>, then using the ideal gas equation to solve for pressure at 425 K</p>	<p>Both the volume and number of molecules are constant, therefore</p> $\frac{P_1}{T_1} = \frac{P_2}{T_2} \Rightarrow \frac{0.70 \text{ atm}}{299 \text{ K}} = \frac{P_2}{425 \text{ K}} \Rightarrow P_2 = 0.99 \text{ atm}$
<p>Part (c):</p> <p>Stating that pressure is caused only by CO<sub>2</sub> molecules colliding <i>with one another</i></p> <p>Using vague or incomplete language, e.g., “CO<sub>2</sub> molecules collide “more” or “molecules exert more force at higher temperature” without specific reference to molecules colliding <i>with walls of the container</i></p> <p>Incorrectly claiming that the volume of the rigid container changes, or that the volume of an individual molecule changes</p>	<p>Faster-moving gas particles collide more frequently with the walls of the container, thus increasing the pressure.</p> <p>or</p> <p>Faster-moving gas particles collide more forcefully with the walls of the container, thus increasing the pressure.</p>

<p>Citing irrelevant information about kinetics (activation energy, orientation of molecules)</p> <p>Reciting a rule or macroscopic observation (e.g., “pressure always increases when temperature increases”) instead of explaining in terms of particle dynamics</p>	
<p>Part (d):</p> <p>Mentioning that both attractive forces <u>and</u> nonnegligible volume of molecules cause the negative deviation from the ideal gas law, when in fact the volume of molecules contributes to a positive deviation</p> <p>Making incorrect statements about ideal gases (particles have no mass, particles do not collide, or STP conditions are required)</p> <p>Misinterpreting the question as a laboratory error analysis and citing faulty equipment as the reason for the observation</p> <p>Implying or explicitly stating that the CO<sub>2</sub> molecules undergo a chemical reaction and/or a change in physical state</p> <p>Giving correct, but irrelevant, information about the conditions under which nonideal gases behave most like ideal gases</p>	<p>The attractive forces between CO<sub>2</sub> molecules result in a pressure that is lower than that predicted by the ideal gas law.</p>

**Based on your experience at the AP<sup>®</sup> 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 carefully and address the question that is actually asked. Sometimes students discussed good chemistry that did not answer the question.
2. Teach students that a complete explanation must include evidence and reasoning, not just reciting a trend like “increasing the temperature makes the pressure of a gas increase.” Allow students to practice their reasoning skills.
3. Incorporate kinetic molecular theory simulations to help students visualize the movement of particles. Use kinetic molecular theory and gas law calculations to illustrate the connection between particle-level and macroscopic behavior.
4. Help students to identify contextual clues, e.g., “motion of the molecules” in part (a) or “in terms of kinetic molecular theory” in part (c), which can help to guide students toward an appropriate line of thinking for their answer.
5. Emphasize the importance of using correct vocabulary. For instance, mass and volume are not interchangeable, and intermolecular and intramolecular mean different things.

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

- Several years’ worth of AP Chemistry free response questions and the associated scoring guidelines are archived on the AP Central website (<https://apcentral.collegeboard.org/courses/ap-chemistry/>). This site also contains sample student responses to exam questions along with specific commentary explaining why each point was or was not earned.
- Teachers can use these online samples and scoring guidelines throughout the year to help students become comfortable in practicing and producing responses within the suggested response time. They can also learn more about the procedures by which their responses will be scored.
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pieces beginning with scaffolded questions that represent what students are ready for at the beginning of the school year and an increased challenge as teacher's progress through the course.

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**Question #5****Task:** Interpretation of a photoelectron spectrum**Topics:** Photoelectron spectroscopy, electron configuration, relationship between photon energy and wavelength**Max. Points:** 4**Mean Score:** 2.64***What were the responses to this question expected to demonstrate?***

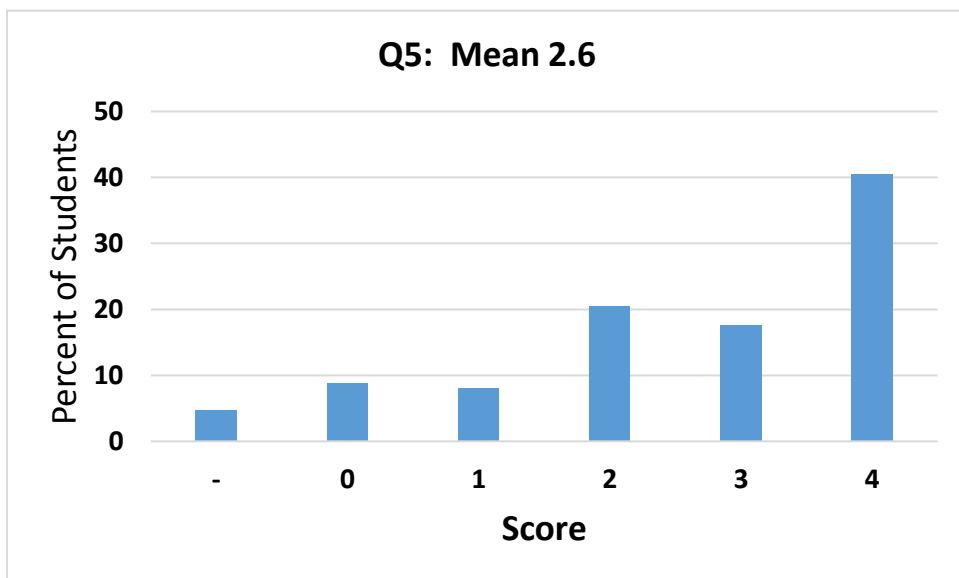
This question uses a photoelectron spectrum as the focal point of questions about electron configuration, chemical identity, and energy-wavelength conversions within the context of atomic structure. All parts of this question address LO 1.7; SP 5.1 and 6.2.

Part (a)(i) asks students to interpret the spectrum to determine the ground-state electron configuration of the element. They must realize that the position and height of each signal in the spectrum corresponds to the energy and relative number of electrons in an orbital shell, respectively. In part (a)(ii) students use the spectrum and/or their electron configuration to identify the unknown element.

Part (b) assesses students' ability to recognize that the PES peak with the lowest energy (on the right of the spectrum) corresponds to removing an electron from the valence shell. The question further assesses students' ability to calculate the wavelength of light associated with this energy. Students need to combine two mathematical relationships ( $E=h\nu$  and  $c=\lambda\nu$ ) and use several constants from the exam booklet.

***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 2.6 out of a possible 4 points, with a standard deviation of 1.4 points. The distribution of points on this question is shown below.



Question 5 was the highest-scoring question on this year's exam. Students generally performed well on all parts of this question, although in aggregate the scores were somewhat stronger in part (a) than in part (b). In part (a) more than half of the responses included the correct ground-state electron configuration and correctly identified the element as calcium. After writing the correct electron configuration, some responses misidentified the element—often as potassium (to the left of calcium) or strontium (below calcium). Students who wrote an incorrect electron configuration in part (a)(i) could earn credit for part (a)(ii) provided that their answer was consistent with that electron configuration. For example, students

writing an electron configuration of  $1s^2 2s^2 2p^6$  and elemental identity of neon did not earn the point for (a)(i) but did earn the point for (a)(ii).

More than half of the responses earned full credit for part (b). Students were not required to specifically state that they chose  $0.980 \times 10^{-18}$  J as the energy required to remove an electron from the valence shell; their selection of energy was implicit in the calculation of photon energy  $E$  in  $E = h\nu$ . Many responses correctly used the relationship  $c = \lambda\nu$  to calculate the wavelength, but some were unable to complete the calculation successfully. Some students attempted to solve the problem using only  $c = \lambda\nu$  and were, therefore, unsuccessful since this approach does not incorporate the concept of energy.

**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> <p>Exclusion of <math>4s</math> and/or inclusion of <math>3d</math> orbitals in the electron configuration</p> <p>Miscounting the electrons, usually by assuming that each line on the vertical axis corresponds to one electron, leading to 10 electrons total (<math>1s^2 2s^2 2p^6</math>)</p>	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2$ or $[\text{Ar}] 4s^2$
<p>Part (a)(ii):</p> <p>Identifying the element as potassium (to the left of calcium) or strontium (below calcium)</p>	Ca
<p>Part (b):</p> <p>Selecting the incorrect energy as corresponding to removing an electron from the valence shell (usually <math>647 \times 10^{-18}</math> J, but sometimes energies from the center of the spectrum or the sum of multiple binding energies)</p> <p>Failing to use the relationship <math>E = h\nu</math>, thereby making it impossible to relate any wavelength to a meaningful energy</p> <p>Solving for <math>\lambda</math> in <math>c = \lambda\nu</math>, but using <math>0.980 \times 10^{-18}</math> J in the place of frequency</p> <p>Solving for <math>\nu</math> in <math>E = h\nu</math>, but reporting <math>\nu</math> as the wavelength</p> <p>Making calculator errors that gave a final answer with an extraordinarily small or extraordinarily large exponent</p>	<div style="border: 1px solid black; padding: 5px;"> <p>Energy (<math>E</math>) required = <math>0.980 \times 10^{-18}</math> J</p> <math display="block">E = h\nu = \frac{hc}{\lambda} \Rightarrow \lambda = \frac{hc}{E}</math> <math display="block">\lambda = \frac{(6.626 \times 10^{-34} \text{ Js})(2.998 \times 10^8 \text{ m s}^{-1})}{0.980 \times 10^{-18} \text{ J}}</math> <math display="block">\lambda = 2.03 \times 10^{-7} \text{ m}</math> </div>

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

1. Continue to teach photoelectron spectroscopy as a tool for probing atomic structure, properties, and identity. Students who are familiar with this experimental technique are much better equipped to answer questions of this type versus those who are unfamiliar with it.
2. Encourage students to pay attention to units, at all times, both in physical constants and in their intermediate work and final answers. Those who assumed that  $\nu$  is a photon wavelength in  $E = h\nu$  should be able to catch their error upon realizing that the final answer would not be expressed in units of meters.
3. Give students plenty of practice using their calculators, particularly in situations with multiple steps or very large/very small exponents. Some students showed the correct mathematical setup but came up with a wildly incorrect order of magnitude in their numerical answers.

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

- Several years' worth of AP Chemistry free response questions and the associated scoring guidelines are archived on the AP Central website (<https://apcentral.collegeboard.org/courses/ap-chemistry/>). This site also contains sample student responses to exam questions along with specific commentary explaining why each point was or was not earned.
- Teachers can use these online samples and scoring guidelines throughout the year to help students become comfortable in practicing and producing responses within the suggested response time. They can also learn more about the procedures by which their responses will be scored.
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- The guidebook *Quantitative Skills in the AP Sciences* (2018) can assist teachers in strengthening their students' quantitative skills throughout the course.
- The AP Chemistry Online Teacher Community (<https://apcommunity.collegeboard.org/web/apchem>) is very active, and there are many discussions concerning teaching tips, techniques, and activities that many teachers have found helpful. It is easy to join, and you can search topics and discussions from previous years.
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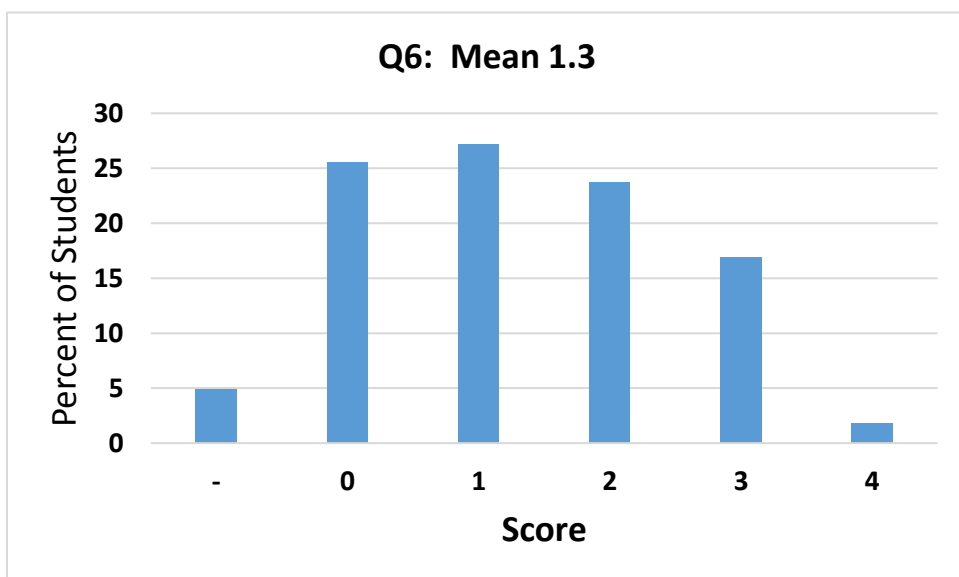
**Question #6****Task:** Evaluate reaction order and potential reaction mechanisms**Topics:** Kinetics, mechanism**Max. Points:** 4**Mean Score:** 1.32**What were the responses to this question expected to demonstrate?**

This question focuses on interpreting kinetic data from the conversion of  $\text{NO}_2$  into  $\text{NO}$  and  $\text{O}_2$  and evaluating whether a proposed mechanism is consistent with the rate law. Part (a) shows three plots ( $[\text{NO}_2]$  vs. time,  $1/[\text{NO}_2]$  vs. time, and  $\ln[\text{NO}_2]$  vs. time) and asks students to explain how they show that the reaction is second order. Only the plot of  $1/[\text{NO}_2]$  vs. time is linear, which is a unique characteristic of second-order reactions (LO 4.2; SP 5.1, 6.4).

In part (b) students must use their knowledge of second-order reactions to write a rate law expression for the reaction (LO 4.2; SP 5.1, 6.4). The remainder of Question 6 addresses LO 4.7; SP 6.5. Part (c)(i) provides a possible two-step reaction mechanism with slow and fast steps labeled. The student is asked to indicate whether the mechanism is consistent with the rate law expression that they wrote in part (b) and to justify their answer. Similarly, part (c)(ii) proposes a different two-step mechanism in which the first step is a fast equilibrium and the second step is slow; students must again indicate whether the mechanism is consistent with the rate law expression that they wrote in part (b) and justify their answer.

**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 1.3 out of a possible 4 points, with a standard deviation of 1.1 points. The distribution of points on this question is shown below.



Most students were successful in part (a) in supporting the claim that the reaction is second order by mentioning the linear relationship between  $1/[\text{NO}_2]$  and time in the second plot. This relationship is unique to second-order reactions. Students were not required to explicitly mention how the other plots are incompatible with a second-order process. Responses that did not receive credit referred to an incorrect plot or failed to refer to the  $1/[\text{NO}_2]$  plot specifically.

Students generally struggled to earn credit for part (b). Common errors exhibited included the omission of a key component like the expression “rate =”, the rate constant  $k$ , or the exponent of 2 for  $[\text{NO}_2]$ . Some students attempted to calculate the numerical value of  $k$ , even though the question does not ask for this information. Others included products in the rate law expression (e.g.,  $\text{rate} = k[\text{NO}]^2[\text{O}_2]$ ), wrote an equilibrium expression ( $\text{rate} = [\text{NO}]^2[\text{O}_2] / [\text{NO}_2]^2$ ), or explicitly used an equilibrium constant in place of a rate constant ( $\text{rate} = K_d[\text{NO}_2]^2$ ).



In part (c)(i), many students failed to directly link the kinetics of the proposed mechanism with the observed rate law of the reaction. Oftentimes an answer would correctly state that the rate law in part (b) is identical to that of the proposed mechanism but fail to show the reasoning that would lead to this conclusion. Credit was awarded only when students referred to the molecularity of the slow (rate-determining) elementary step in the mechanism. Part (c)(ii) was the most challenging section of Question 6 because it integrates the concept of equilibrium with kinetic analysis. Most responses made the invalid direct substitution of  $[N_2O_4] = [NO_2]$  or  $[N_2O_4] = [NO_2]^2$  rather than the correct substitution  $[N_2O_4] = K_{eq}[NO_2]^2$ . There is a second valid method of solving this problem that uses the relationship  $k_{reverse}[N_2O_4] = k_{forward}[NO_2]^2$  to arrive at the substitution  $[N_2O_4] = k_{forward}/k_{reverse} [NO_2]^2$ , but this approach was rarely seen.

**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>Using indirect or incomplete reasoning, sometimes discussing the first and third plots without any mention of the second plot</p> <p>Referring to the stoichiometric coefficient of 2 for <math>NO_2</math> in the balanced chemical equation, instead of the data in the plots</p>	<p>The linear graph of <math>\frac{1}{[NO_2]}</math> vs. time indicates a second-order reaction.</p>
<p>Part (b):</p> <p>Using the concentration of products in the experimental rate law expression, e.g. <math>rate = k[NO][NO_3]</math></p> <p>Confusing <math>k</math> with an equilibrium constant, as in <math>rate = K_c[NO_2]^2</math></p> <p>Confusing rate law expression with an equilibrium constant expression, as in <math>rate = K_{eq} \frac{[NO]^2 [O_2]}{[NO_2]^2}</math></p>	<p><math>rate = k[NO_2]^2</math></p>
<p>Part (c)(i):</p> <p>Stating that the proposed mechanism follows a second-order rate law without referring to the molecularity of the slow (rate-limiting step)</p> <p>Adding the individual steps of the mechanism to generate the original reaction, then stating that the process is second-order because the stoichiometric coefficient for <math>NO_2</math> is 2:</p> <ol style="list-style-type: none"> <li>1. <math>NO_2 + NO_2 \rightarrow NO + NO_3</math> <i>slow</i></li> <li>2. <math>NO_3 \rightarrow NO + O_2</math> <i>fast</i></li> <li>3. <math>2 NO_2 \rightarrow 2 NO + O_2</math></li> </ol>	<p>Yes. Step 1 is slow, therefore it is the rate-determining step of this mechanism. The rate law of this elementary reaction is <math>rate = k[NO_2][NO_2] = k[NO_2]^2</math>, which is consistent with the second-order rate law in part (b).</p>

Common Misconceptions/Knowledge Gaps	Responses that Demonstrate Understanding
<p>Part (c)(i):</p> <p>Stating that the proposed mechanism follows a second-order rate law without referring to the molecularity of the slow (rate-limiting step)</p> <p>Referring only to the stoichiometric coefficient of 2 for NO<sub>2</sub> in the balanced chemical equation</p> <p>Making invalid substitutions like [N<sub>2</sub>O<sub>4</sub>] = [NO<sub>2</sub>] or [N<sub>2</sub>O<sub>4</sub>] = [NO<sub>2</sub>]<sup>2</sup></p> <p>Expressing the rate constant for every process (the overall reaction and the forward/reverse of every mechanistic step) as a numerically identical <i>k</i>, giving:</p> $k[\text{N}_2\text{O}_4] = k[\text{NO}_2]^2 \quad (\text{from the first mechanistic step})$ $\text{rate} = k[\text{N}_2\text{O}_4] \quad (\text{from the second mechanistic step})$ <p>therefore, rate = <math>k[\text{N}_2\text{O}_4] = k[\text{NO}_2]^2</math>, which is identical to the rate law expression in part (b)</p>	<p>Yes. Step 2 is slow, therefore it is the rate-determining step of this mechanism. The rate law of this elementary reaction is rate = <math>k[\text{N}_2\text{O}_4]</math>. Because N<sub>2</sub>O<sub>4</sub> is an intermediate, it cannot appear in the rate law of the overall reaction.</p> <p>Because <math>K_{eq} = \frac{[\text{N}_2\text{O}_4]}{[\text{NO}_2]^2}</math> in step 1, [N<sub>2</sub>O<sub>4</sub>] = <math>K_{eq}[\text{NO}_2]^2</math>.</p> <p>Then, substituting <math>K_{eq}[\text{NO}_2]^2</math> for [N<sub>2</sub>O<sub>4</sub>] in the rate law of step 2 gives rate = <math>(k K_{eq})[\text{NO}_2]^2</math>, which is consistent with the rate law in part (b).</p>

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

1. Give students practice in identifying the kinetic order of a reaction, particularly from graphical information, so they can quickly and correctly make identifications based upon the quantity that is being plotted. These skills can be reinforced in the laboratory.
2. Emphasize the important differences between commonly-confused terms like “rate constant” vs. “rate” or rate constant (*k*) vs. equilibrium constant (*K*).
3. Be sure that your curriculum involves the interpretation of reaction mechanisms, especially those with a fast equilibrium step followed by a slow step. Students should have the opportunity to practice justifying experimental rate laws based on molecular collisions described by rate laws and elementary steps.
4. Encourage students to be as specific as possible in wording their responses. For example, in part (a), vague responses like “the data is linear” (without reference to which data from the three plots) are rarely awarded credit. Give them examples of scientific language commonly used to describe chemical phenomena and data so as to avoid ambiguous terms like “a plot that is mostly linear” or “the data has a true slope.”
5. Include questions written in the style of a free-response section in your own classroom assessments. The more practice students get in articulating their thoughts—particularly on topics like kinetics that can sometimes be more challenging—the better prepared they will be for the AP Exam.

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

- Several years’ worth of AP Chemistry free response questions and the associated scoring guidelines are archived on the AP Central website (<https://apcentral.collegeboard.org/courses/ap-chemistry/>). This site also contains sample student responses to exam questions along with specific commentary explaining why each point was or was not earned.
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the types of questions on the AP Exam. This includes practice FRQs for teachers to use as formative assessment pieces beginning with scaffolded questions that represent what students are ready for at the beginning of the school year and an increased challenge as teacher's progress through the course.

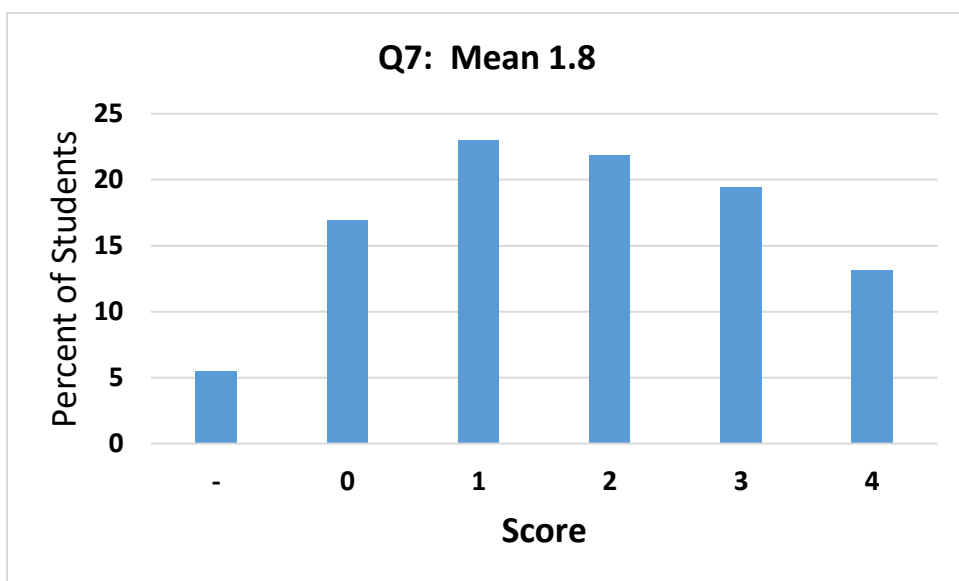
- The guidebook *Quantitative Skills in the AP Sciences* (2018) can assist teachers in strengthening their students' quantitative skills throughout the course.
- The AP Chemistry Online Teacher Community (<https://apcommunity.collegeboard.org/web/apchem>) is very active, and there are many discussions concerning teaching tips, techniques, and activities that many teachers have found helpful. It is easy to join, and you can search topics and discussions from previous years.
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**Question #7****Task:** Interpret experimental data in a redox titration**Topics:** Oxidation number, laboratory measurements, stoichiometry**Max. Points:** 4**Mean Score:** 1.78***What were the responses to this question expected to demonstrate?***

This question deals with the theory and practice of a redox titration in which  $\text{MnO}_4^-$  reacts with oxalic acid,  $\text{H}_2\text{C}_2\text{O}_4$ . In part (a) students are required to determine the species that is reduced in the titration reaction and use oxidation numbers to justify their selection (LO 3.12; SP 2.2, 2.3, 6.4). Part (b) assesses their ability to read a buret, both at the beginning and at the end point of the titration, and to use those readings to determine the volume of  $\text{MnO}_4^-$  solution that was delivered during the experiment. In part (c) students use that volume of titrant to determine the number of moles of  $\text{MnO}_4^-$  that reacted during the titration. Part (d) requires students to demonstrate their understanding of titration procedure and the limitations of the available equipment. Using a much more dilute solution of titrant (by a factor of  $\sim 16$ ) would require a large amount of titrant (431 mL) that would exceed the capacity of the buret. Parts (b) through (d) all address LO 1.20; SP 4.2, 5.1, and 6.4.

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

The mean score for Question 7 was 1.8 out of a possible 4 points, with a standard deviation of 1.3 points. The distribution of points on this question is shown below.



Most students correctly interpreted the chemical equation to determine in part (a) that the permanganate ion is reduced in the titration reaction. They assigned correct oxidation numbers to the manganese atom in both the permanganate and  $\text{Mn}^{2+}$  ions. Responses with incorrect oxidation numbers on manganese did not receive credit. Part (b) had a range of acceptable answers, but the best ones took the reading from the bottom of the meniscus to the nearest  $\pm 0.01$  mL. A common error was to read the scale on the buret from the bottom upwards rather than from the top downwards, for example giving an initial reading of 4.65 mL rather than 3.35 mL. Units were not required to receive credit, but they had to be correct if they were included.

In part (c) most students correctly multiplied the volume of the titrant solution by its concentration. Some, however, converted incorrectly between units of milliliters and liters or did not convert at all. Others appended a multiplicative factor of  $5/2$  (the molar ratio of reactants) at the end of their calculation. Some responses took the more circuitous route of calculating the number of moles of oxalic acid that was present in the original sample and then determining the number

of moles of  $\text{MnO}_4^-$  required to react completely with that sample. This approach earned credit if done correctly. The answer to part (c) was required to have the correct number of significant figures to receive the point. The majority of responses to part (d) correctly indicated that using a highly diluted solution of titrant would be unreasonable, but varied in their quality and level of detail. The best answers specifically mentioned the limited total capacity of the buret and/or the need to refill the buret eight times, although a numerical calculation was not required 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>Misidentifying the species that is reduced and/or miscalculating oxidation number</p> <p>Identifying a product as the species that was reduced</p> <p>In a polyatomic ion, equating the oxidation number of an individual atom with the overall ionic charge of the species (e.g., the oxidation number of Mn in <math>\text{MnO}_4^-</math> is -1)</p> <p>Reversing the definition of reduction (loss of electrons, rather than gain of electrons)</p> <p>Interpreting a redox process as a gain or loss of protons, rather than electrons</p>	<p><math>\text{MnO}_4^-</math> is reduced to <math>\text{Mn}^{2+}</math> as the oxidation number of Mn changes from +7 to +2, indicating a gain of 5 electrons.</p>
<p>Part (b):</p> <p>Reading the buret scale from the bottom up, rather than from the top down (initial and final readings of 4.65 mL and 30.45 mL, respectively)</p> <p>Misreading the markings (e.g., 3.45 mL for the initial reading)</p> <p>Interpreting the buret tick marks as units of 1 mL, rather than units of 0.1 mL</p> <p>Failing to subtract the initial reading from the final reading to determine the volume of titrant that was dispensed</p>	<p><math>29.55 \text{ mL} - 3.35 \text{ mL} = 26.20 \text{ mL}</math></p>
<p>Part (c)</p> <p>Using an incorrect volume of titrant in the calculation, most often 50.0 mL (the total capacity of the buret), 3.35 mL (the initial reading of the buret), or 29.55 mL (the final reading of the buret)</p> <p>Multiplying the result by 5/2 (the molar ratio of oxalic acid to permanganate ion in the balanced chemical equation)</p> <p>Multiplying the result by 2 (the stoichiometric coefficient of permanganate ion in the balanced chemical equation)</p> <p>Converting incorrectly (or not at all) between mL and L</p> <p>Using the incorrect number of significant figures</p>	<p><math>(0.02620 \text{ L})(0.0235 \text{ mol/L}) = 0.000616 \text{ mol}</math></p>

<i>Common Misconceptions/Knowledge Gaps</i>	<i>Responses that Demonstrate Understanding</i>
<p>Part (d)</p> <p>Making vague or ambiguous statements such as “it would take too much” or “it is too dilute” or “there is not enough”</p> <p>Referring to irrelevant information such as the kinetics of the reaction or the absence of a base (confusing the reaction with an acid-base titration)</p> <p>Misinterpreting the experiment, thinking that the student was adding more titrant as a continuation of the first experiment, rather than beginning a new experiment</p>	<p>No. The 0.00143 <i>M</i> titrant solution is so dilute that the volume of titrant needed to reach the end point would be much greater than the 50 mL capacity of the buret.</p>

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

1. Illustrate the methods used to identify the species that are reduced and oxidized in a redox reaction, particularly with specific atoms in polyatomic ions.
2. Practice the technique of reading a buret, paying attention to the correct number of significant figures, units, and meniscus location.
3. Have students propose an appropriate concentration of their titrant solution or give them situations where they need to determine whether a given volume/concentration is practical.
4. Ask students to explain, in their own words, when it is and isn't appropriate to perform calculations that use the stoichiometric coefficients from a chemical reaction.

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

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