Chief Reader Report on Student Responses:

2021 AP® Chemistry Free-Response Questions

- Number of Students Scored 135,997
- Number of Readers 413
- Score Distribution

Exam Score	N	%At
5	15,195	11.2
4	22,355	16.4
3	32,244	23.7
2	33,648	24.7
1	32,555	23.9

- Global Mean 2.66

The following comments on the 2021 free-response questions for AP® 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.

Question #1   Task: Analysis of methanoic acid   **Topics:** Equilibrium, Lewis structure, gas laws

Max. Points: 10   **Mean Score:** 3.93

### *What were the responses to this question expected to demonstrate?*

Question 1 presents a suite of questions on the reactions and structure of methanoic acid, HCOOH. Part (a) asks the student to write the equilibrium constant expression for the acid ionization reaction of HCOOH. This question addresses Learning Objective SAP-9.C and Science Practice 5.B from the *AP Chemistry Course and Exam Description*. The K_a expression is used in part (b) to calculate the pH of a solution of HCOOH of known concentration. Two points are possible: one for determining the concentration of H_3O^+ (SAP-9.C, 5.A) and one for the correct pH (SAP-9.C, 5.F). Part (c) then asks for a drawing of the complete Lewis diagram for HCOOH (SAP-4.A, 3.B).

Methanoic acid reacts with hydrazine (H_2NNH_2) in an acid-base reaction that the student must describe with a net ionic equation in part (d)(i) (TRA-1.B, 5.E). In part (d)(ii), the student determines whether the resulting solution is acidic, basic, or neutral and explains why (SAP-9.D, 6.D).

Methanoic acid also undergoes a decomposition reaction in the presence of a catalyst. In part (e), the student must determine, with evidence, if it is a redox reaction (TRA-2.A, 6.D). The $H_2(g)$ and $CO_2(g)$ products increase the total pressure inside the reaction vessel, as shown in a graph. The student needs to calculate the total number of moles of CO_2 produced in the reaction in part (f). This part is worth two points: one for the correct pressure of CO_2 (SPQ-4.A, 5.F), and one for the correct number of moles of CO_2 (SAP-7.A, 5.F). As a follow-up, part (g) asks about how (if at all) the amount of catalyst changes as the reaction proceeds (ENE-1.A, 1.B).

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 3.9 out of a possible 10 points, with a standard deviation of 2.6 points. The distribution of scores on this question is shown below. Question 1 had the lowest average among the three long (10-point) free-response questions. Credit was earned most often on parts (a), (b), (c), and (f), while parts (d) and (g) were the most challenging.
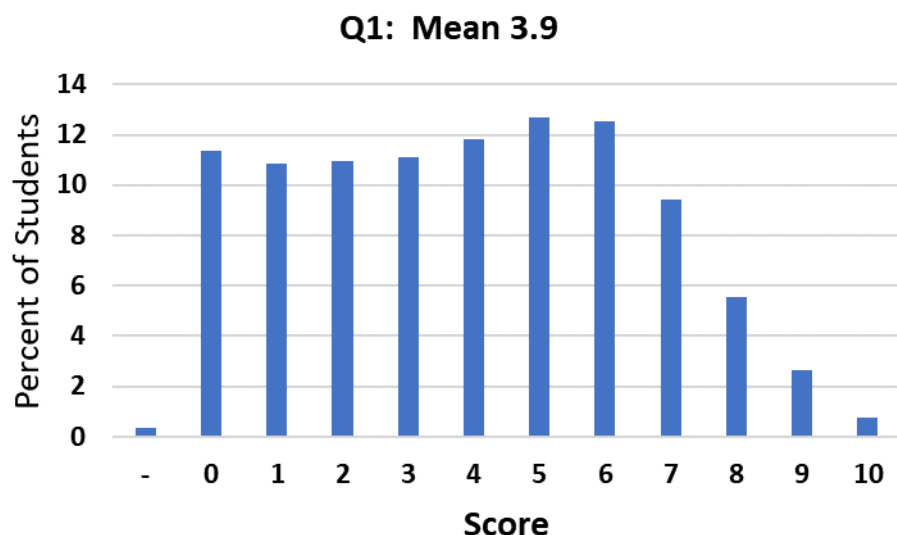
Part (a) was an accessible entry point for most students. The "$K_a =$" component was required as part of a complete mathematical expression. The algebraic rearrangement and substitution on part (b) also generally went well. Responses that earned less than full credit contained either computational errors (omitting either the square root operation or the division by 0.25) or conceptual errors (treating HCOOH as a strong acid or calculating pH from the natural log of [H_3O^+]). Some students interpreted the formula HCOOH as a hydroxide. In part (c) students were often successful in drawing the correct Lewis structure for HCOOH, although some used an incorrect number of valence electrons.

Responses to part (d)(i) contained a variety of errors. Students often treated the weak acid-weak base neutralization reaction as something other than a proton transfer process, while others used H_2O, H^+, or OH^- as reactants. Part (d)(ii) was the lowest-scoring part of Question 1. A common error was treating H_2NNH_2 as a weak acid rather than a weak base. There were also many unsuccessful attempts at calculating the exact numerical pH of the solution with the Henderson-Hasselbalch equation and other incorrect methods.

Part (e) was surprisingly challenging for students. Some interpreted the formula HCOOH as a peroxide. Many did not identify the process as redox, and those who did either assigned oxidation numbers incorrectly or did not assign them at all. Claims about hydrogen being reduced or carbon being oxidized had to be supported by evidence to receive credit. In part (f), most responses earned one out of the two points possible. Very few recognized that the partial pressure of CO_2 was half the total pressure inside the vessel, although most correctly used the ideal gas law to convert a partial pressure to a number of moles. Some students struggled with selecting the appropriate version of the gas constant R and/or converting between Celsius and Kelvin temperatures correctly. In part (g), most responses correctly stated that the amount of catalyst in the overall reaction remains the same. The best explanations were correct, clear, and concise. Those that were ambiguous or only discussed activation energy did not 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*
Part (a): • Including H_2O in the expression: $$K_a = \frac{[H_3O^+]\,[HCOO^-]}{[HCOOH]\,[H_2O]}$$ • Missing ionic charges: $K_a = \dfrac{[H_3O]\,[HCOO]}{[HCOOH]}$ • Writing the inverted expression: $$K_a = \frac{[HCOOH]}{[H_3O^+]\,[HCOO^-]}$$ • Omitting "$K_a =$" at the beginning of the expression	$$K_a = \frac{[H_3O^+][HCOO^-]}{[HCOOH]}$$ Note: H^+ may be used interchangeably with H_3O^+.

Part (b):

- Dividing, rather than multiplying, the K_a by 0.25:

  $$\frac{1.8 \times 10^{-4}}{0.25} = x^2 \Rightarrow x = 2.7 \times 10^{-2}$$

  $pH = -\log(2.7 \times 10^{-2}) = 1.57$

- Omitting the factor of 0.25:

  $$1.8 \times 10^{-4} = x^2 \Rightarrow x = 1.3 \times 10^{-2}$$

  $pH = -\log(1.3 \times 10^{-2}) = 1.87$

- Omitting the exponent:

  $$1.8 \times 10^{-4} = \frac{x}{0.25} \Rightarrow x = 4.5 \times 10^{-5}$$

  $pH = -\log(4.5 \times 10^{-5}) = 4.35$

- Omitting the square root operation:

  $$1.8 \times 10^{-4} = \frac{x^2}{0.25} \Rightarrow x = 4.5 \times 10^{-5}$$

  $pH = -\log(4.5 \times 10^{-5}) = 4.35$

- Treating HCOOH as a strong acid:
  $pH = -\log(0.25) = 0.60$

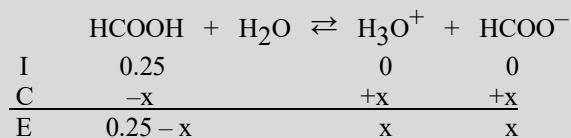- Treating HCOOH as a strong base:
  $pOH = -\log(0.25) = 0.60$
  $pH = 14 - pOH = 13.40$

- Mis-applying the Henderson-Hasselbalch equation:

  $$pH = -\log(1.8 \times 10^{-4}) + \log\frac{0.25}{0.25} = 3.74$$

- Using natural log rather than $\log_{10}$ to relate pH to $[H_3O^+]$:
  $pH = -\ln(0.0067) = 5.00$

$$HCOOH + H_2O \rightleftharpoons H_3O^+ + HCOO^-$$

	HCOOH	H₂O	H₃O⁺	HCOO⁻
I	0.25		0	0
C	$-x$		$+x$	$+x$
E	$0.25 - x$		x	x

Let $[H_3O^+] = x$, then $1.8 \times 10^{-4} = \dfrac{x^2}{(0.25 - x)}$

Assume $x \ll 0.25$, then $1.8 \times 10^{-4} = \dfrac{x^2}{0.25} \Rightarrow$

$x = 0.0067$ M
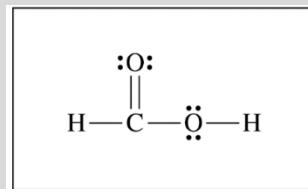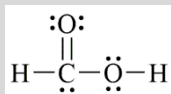
$pH = -\log[H_3O^+] = -\log(0.0067) = 2.17$

Part (c):

- Including the correct number of valence electrons, but violating the octet rule:
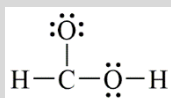
- Including too many or too few valence electrons, e.g.,:

Part (d)(i):	$H_2NNH_2(aq) + HCOOH(aq) \rightarrow H_2NNH_3^{+}(aq) + HCOO^{-}(aq)$
• Omitting ionic charges: $H_2NNH_2 + HCOOH \rightarrow H_2NNH_3 + HCOO$ • Using H^+ or OH^- as a reactant: $H^+ + H_2NNH_2 \rightarrow H_2NNH_3^{+}$ or $OH^- + HCOOH \rightarrow H_2O + HCOO^-$	

Part (d)(ii):	Acidic. The K_a of $H_2NNH_3^{+}$ is greater than the K_b of $HCOO^-$, so the production of $H_3O^{+}(aq)$ occurs to a greater extent than the production of $OH^-(aq)$.
• Treating HCOOH and H_2NNH_2 both as weak acids • Comparing the magnitude of 1.8×10^{-4} vs. 1.3×10^{-6} without providing any further explanation • Claiming that $[H_3O^{+}] > [OH^-]$, without any explanation	

Part (e):	• Yes. The oxidation number of hydrogen changes from +1 in HCOOH to zero in H_2. or • Yes. The oxidation number of carbon changes from +2 in HCOOH to +4 in CO_2.
• Claiming that decomposition reactions are always redox • Asserting, without evidence, that certain atoms are reduced or oxidized • Assigning incorrect oxidation numbers to one or more atoms	

Part (f):	*24 atm total × 1 atm CO_2 / 2 atm of product = 12 atm CO_2* *$PV = nRT$* $n = \dfrac{PV}{RT} = \dfrac{(12 \text{ atm})(4.3 \text{ L})}{(0.08206 \text{ L atm mol}^{-1}\text{ K}^{-1})(298 \text{ K})} = 2.1 \text{ mol CO}_2$
• Using 24 atm, rather than 12 atm, as the partial pressure of CO_2 • Using $R = 8.314 \text{ J mol}^{-1}\text{ K}^{-1}$ or $R = 62.36 \text{ L torr mol}^{-1}\text{ K}^{-1}$ • Converting °C to Kelvins incorrectly, or not at all • Using the standard molar volume of 22.4 L mol^{-1}	

Part (g):	It would remain the same. In a catalyzed reaction the net amount of catalyst is constant.
• Discussing the effect of a catalyst on the rate of reaction, rather than focusing on the conservation of the material • Claiming incorrectly that the catalyst "is not involved in the reaction" or "does not react"	

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

1. Emphasize acid-base chemistry as a proton transfer process in which the ionic charges of species also changes.
2. Highlight the various ways of describing organic acids (Lewis structure and formula units CO_2H or COOH). Some students interpreted the formula HCOOH as a peroxide or a hydroxide compound.
3. Require students to use units in all of their intermediate calculations, to avoid simple errors such as using the incorrect version of the gas constant R or using degrees Celsius instead of Kelvins.
4. Practice drawing Lewis structures that are clear and easy to understand. Avoid depicting a bond as both a line and a pair of electrons simultaneously ($\cdot-\cdot$ or $\div$). Including the correct number of valence electrons is essential.
5. Demonstrate how to use the values of K_a and K_b to (a) evaluate whether a chemical species will act as an acid or as a base in aqueous solution and (b) predict the predominant direction of reaction for weak acid-weak base neutralization reactions.
6. Strengthen students' skills in writing clear answers that include relevant details. Responses like "The reaction is redox because oxidation numbers change" or "The catalyst speeds up the reaction" did not receive credit.

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

- Teachers can use AP Classroom to direct students to the AP Daily videos on Topics 2.5, 4.2, 4.5, 4.7, 2.5, 3.4, 5.11, 8.3, and 8.4.
- Teachers can use AP Classroom to direct students to the Unit 5 Faculty Lecture that discusses the role of catalysis in biological reactions.
- To help students with improving the clarity and specificity of their written responses, teachers can use the "Write This, Not That—Updated 2019" compiled by Nora Walsh, available in the Resources Library of the Online Teacher Community.
- Teachers can assign topic questions and/or personal progress checks in AP Classroom to monitor student progress and identify areas for additional instruction or content and skill development.

Question #2 **Task:** Analysis of Si and its compounds

Topics: Atomic structure and thermodynamics

Max. Points: 10

Mean Score: 4.66

### What were the responses to this question expected to demonstrate?

Question 2 deals with the atomic structure of silicon and the properties of silicon-containing compounds. In part (a)(i), the student is asked to interpret a mass spectrum to determine the number of subatomic particles in the most abundant isotope of Si (SPQ-1.B, 5.D). Part (a)(ii) asks for the ground-state electron configuration of Si (SAP-1.A, 3.B). In part (b), the student must use principles of interparticle forces to explain the relative boiling points of SiH_4 vs. SiO_2 (SAP-5.B, 6.E).

Part (c) asks for the balanced chemical equation that describes the decomposition of SiH_4 into elemental silicon and hydrogen gas (TRA-1.B, 5.E). These two products have different absolute molar entropies, as shown in a data table, and the student is asked to explain why $S°$ of solid Si is less than that of H_2 gas (ENE-4.A, 6.E). The absolute entropies are used in part (e) to calculate the standard entropy change of the reaction (ENE-4.B, 5.F). Part (f) then asks for an explanation for why the reaction occurs only at high temperatures (ENE-4.D, 4.A), despite being thermodynamically favorable at all temperatures.

Part (g) shows an incomplete photoelectron spectrum of silicon, which must be completed by drawing the missing peak corresponding to the electrons in the *3p* subshell (SAP-1.B, 3.A). Part (h) asks the student to compare the first ionization energies of Si and Ge using principles of atomic structure (SAP-2.A, 6.C). Finally, part (i) involves a calculation of the energy of a single photon of a given wavelength (SAP-8.B, 5.F).

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

The mean score for Question 2 was 4.7 out of a possible 10 points, with a standard deviation of 2.3 points. The distribution of scores on this question is shown below. Question 2 had the highest average among the three long (10-point) free-response questions. Most responses earned the point in parts (a)(i) and (a)(ii), reflecting a strong understanding of atomic composition and electron configuration.

Q2: Mean 4.7
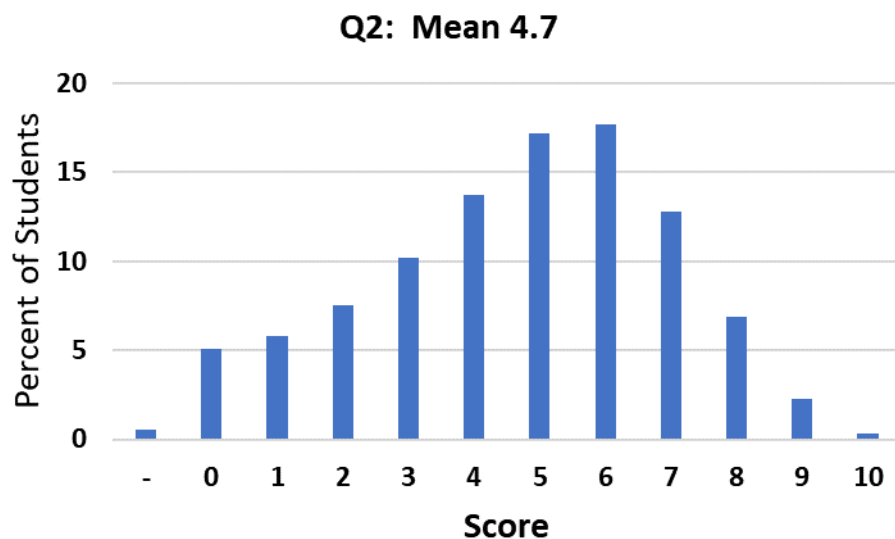
Part (b) was the most challenging part of Question 2. Students often struggled to identify the predominant interparticle forces in the two substances. Many responses invoked hydrogen bonding in SiH_4 or dipole-dipole forces in SiO_2, while others focused on the relative polarizability (size / number of electrons) of the SiH_4 vs. SiO_2 formula unit. Very few recognized SiO_2 as a network covalent solid.

A majority of responses to part (c) received credit for providing the correct balanced equation for the decomposition of SiH_4. The most common error was writing an unbalanced equation. Part (d) was a difficult question. Most responses failed to earn the point because they gave an ambiguous rationale or did not provide one at all. Many students correctly claimed that gases have higher entropy than solids but simply stopped at that assertion without providing any further explanation. Comparative terms like "more random," "more chaotic," and "more disorganized" were common, although in a few impressive cases entropy was defined as a measure of the dispersion of matter or number of available microstates. The responses to part (e) had mixed success. Most correctly used the S° values to calculate $\Delta S°$, but many failed to use the stoichiometric coefficient of H_2 from the balanced chemical equation in part (c). In part (f), many responses focused entirely on the phrase "the reaction occurs only at high temperatures" and tried to build an argument based upon the algebraic sign and relative magnitudes of $\Delta H°$ and $\Delta S°$. They overlooked the first part of the prompt indicating that the reaction is thermodynamically favorable at all temperatures. Relatively few students answered correctly in terms of activation energy or kinetic control.

Most students were successful in drawing a peak with the correct location and height in the photoelectron spectrum in part (g), representing both the number and appropriate shell/subshell of *3p* electrons. Part (h) was much more challenging. Most students cited a periodic trend correctly but simply stopped at that point. A complete explanation based upon principles of atomic structure (orbital shell occupancy and Coulombic attraction) was required to receive credit. Most responses to part (i) had the correct setup, with the majority earning credit. The correct scientific notation mantissa of 4.97 was almost always present, but the power of 10 varied widely, suggesting that students had difficulty keying in and manipulating exponents with their calculators.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
Part (a)(i): • Providing the number 14 by itself, rather than explicitly stating 14 protons and 14 neutrons • Using 28, the atomic mass • Using 92, the percent abundance of ^{28}Si	14 protons and 14 neutrons
Part (a)(ii): • Incomplete labeling of every shell or subshell, e.g.: $s^2\,2s^2\,2p^6\,3s^2\,3p^2$ or $1s^2\,2s^2p^6\,3s^2p^2$	• $1s^2\,2s^2\,2p^6\,3s^2\,3p^2$ or • $[Ne]\,3s^2\,3p^2$

Part (b):
 	
• Failing to recognize SiO_2 as a network covalent compound:
 	
   o "SiO_2 has stronger London dispersion forces than SiH_4 because SiO_2 is more polarizable / has more electrons / is larger."
 	
   o "SiO_2 has dipole-dipole forces."
 	
   o "SiO_2 is ionic."
 	
• Claiming that SiH_4 has hydrogen bonding.
 	
• Comparing the bond dissociation energy of the Si—H bond in SiH_4 to that of the Si=O bond in SiO_2.
	SiH_4 is composed of molecules, for which the only intermolecular forces are London dispersion forces. SiO_2 is a network covalent compound with covalent bonds between silicon and oxygen atoms. London dispersion forces are much weaker than covalent bonds, so SiH_4 boils at a much lower temperature than SiO_2.

Part (c): • Neglecting to balance the equation: $SiH_4 \rightarrow Si + H_2$	$SiH_4(g) \ \rightarrow \ Si(s) \ + \ 2\,H_2(g)$
Part (d): • Restating the prompt as the only form of explanation: "The entropy of the gas is greater than the entropy of the solid." • Providing an incomplete explanation: "gases occupy a greater volume than solids" or "gases have higher entropy than solids."	The $H_2(g)$ molecules are more highly dispersed than the $Si(s)$ atoms and, therefore, have a higher absolute molar entropy. Silicon is a solid; therefore, its atoms are in fixed positions, are less dispersed, and have a lower absolute molar entropy.
Part (e): • Missing the stoichiometric coefficient on H_2: $\Delta S° = (18 + 131) - 205 = -56$ J/(mol$_{rxn}$·K) • Reversing the sign or order of products and reactants: $\Delta S° = 205 - (18 + 2(131)) = -75$ J/(mol$_{rxn}$·K)	$\Delta S^{\circ}_{rxn} = (18 + 2(131)) - 205 = +75$ J/(mol$_{rxn}$·K)

Part (f):
 	
• Focusing on thermodynamics rather than kinetics:
 	
   o "Because ΔS is positive in part (e), ΔH must be positive, so ΔG is negative only at high temperatures."
 	
   o "Breaking bonds is an endothermic process."
	High temperature is required for the reactant particles to have sufficient thermal energy to overcome the activation energy of the reaction.

• Defining kinetics or kinetic molecular theory, without any explicit or implicit mention of activation energy	
Part (g): • Drawing a peak that has a relative height of six electrons (showing a completely-filled *3p* subshell rather than the partially-filled *3p* subshell found in an atom of Si)	

Part (h):
 	
• Citing a periodic trend without providing an explanation that uses principles of atomic structure:
 	
  o Ge is larger than Si.
 	
  o Ge has more orbitals than Si.
 	
  o Ge is less electronegative than Si.
 	
  o Ge has more shielding/lesser effective nuclear charge than Si.
 	
  o Ge is below Si in the periodic table.
	The valence electrons of a Ge atom occupy a higher shell ($n = 4$) than those of a Si atom ($n = 3$), so the average distance between the nucleus and the valence electrons is greater in Ge than in Si. This greater separation results in weaker Coulombic attractions between the Ge nucleus and its valence electrons, making them less tightly bound and, therefore, easier to remove compared to those in Si.

Part (i): • Substituting wavelength, instead of frequency, into the equation for photon energy: $E = h\nu = (6.626 \times 10^{-34} \text{ J·s}) (4.00 \times 10^{-7} \text{ m}) = 2.65 \times 10^{-40} \text{ J}$ • Providing the incorrect exponent in the answer: $4.97 \times 10^{-n} \text{ J}$ (where *n* is an integer other than 19)	$E = h\nu = h\left(\dfrac{c}{\lambda}\right) = 6.626 \times 10^{-34} \text{ J·s} \left(\dfrac{2.998 \times 10^{8} \text{ m s}^{-1}}{4.00 \times 10^{-7} \text{ m}}\right)$ $E = 4.97 \times 10^{-19} \text{ J}$

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

1. Compare and contrast boiling (disruption of intermolecular attractions) versus decomposition (breaking of covalent bonds). Illustrate the differences with multiple representations such as pictures and chemical equations.
2. Encourage students to use the AP curriculum definition of entropy (dispersion of energy or matter) rather than colloquial ones like "disorder" or "chaos" to deepen their understanding.
3. Insist that students provide complete explanations that follow the claim / evidence / reasoning model. Reciting a fact, rule, or trend by itself is an incomplete explanation.
4. Emphasize the foundational reasoning (atomic structure, Coulomb's law) that underpins periodic trends.

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

- Teachers can use AP Classroom to direct students to the AP Daily videos on Topics 1.5, 1.8, 3.1, 3.2, 3.12, 9.1, 9.2, and 9.4.
- Teachers can use AP Classroom to direct students to Review Session 4: Examining Coulomb's Law, Periodicity, and Intermolecular Forces.
- Teachers can use the self-paced webinar, Exploring Atomic Structure Using Photoelectron Spectroscopy (PES) Data, available on AP Central, for strategies on how to interpret and reason with PES data and atomic structure.
- Teachers can refer to the article "Disorder in Thermodynamic Entropy" by Frank L. Lambert and the discussion on APTeach.org on Explaining Entropy Changes on the Particle Level for helping students use appropriate terminology and explanations for concepts related to entropy.
- To help students with the claim / evidence / reasoning (CER) model and argumentation skills in chemistry, teachers can access the article on ChemEd X by Ben Meacham.
- Teachers can assign topic questions and/or personal progress checks in AP Classroom to monitor student progress and identify areas for additional instruction or content and skill development.

Question #3 **Task:** Determine molar concentration of $CuSO_4$ **Topics:** Stoichiometry, laboratory technique, Beer-Lambert law

**Max. Points:** 10 **Mean Score:** 4.44

What were the responses to this question expected to demonstrate?

Question 3 illustrates two different methods for determining the concentration of $CuSO_4$ in an aqueous solution: gravimetric analysis and spectrophotometry. The student begins in part (a) by providing the net ionic equation for the precipitation of $BaSO_4$ (TRA-1.B, 5.E) followed by calculating the number of moles of precipitate that formed, based upon a data table. Part (b) is worth two points: the first for calculating the mass of the precipitate (SPQ-1.A, 5.F) and the second for calculating the number of moles of $BaSO_4$ (SPQ-4.A, 5.F). This information is used in part (c) to calculate the molarity of the original $CuSO_4$ solution (SPQ-3.A, 5.F).

The spectrophotometry experiment begins with the creation of a calibration curve using samples of $CuSO_4(aq)$ of known concentration that are created by diluting a stock solution. The volume of stock solution required to reach a target volume and concentration is calculated in part (d) (SPQ-3.A, 5.F), and then in part (e) the student writes a brief experimental procedure for preparing that solution (two points; both SPQ-3.A, 2.C). The calibration curve is shown in a graph and then used in part (f) to determine the concentration of a solution of $CuSO_4$ based upon its absorbance (SAP-8.C, 5.D). Part (g) is a two-point question about the effect of residual water inside the cuvette; the first point is awarded for predicting that the measured concentration will be less than the actual concentration (SAP-8.C, 6.A) and the second point is for a valid justification (SAP-8.C, 6.G).

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

The mean score for Question 3 was 4.4 out of a possible 10 points, with a standard deviation of 2.8 points. The distribution of scores on this question is shown below. Nearly every student attempted to answer at least one part of this question. Parts (d) and (f) were accessible to most students, as were the first points in parts (b) and (g).

Q3: Mean 4.4
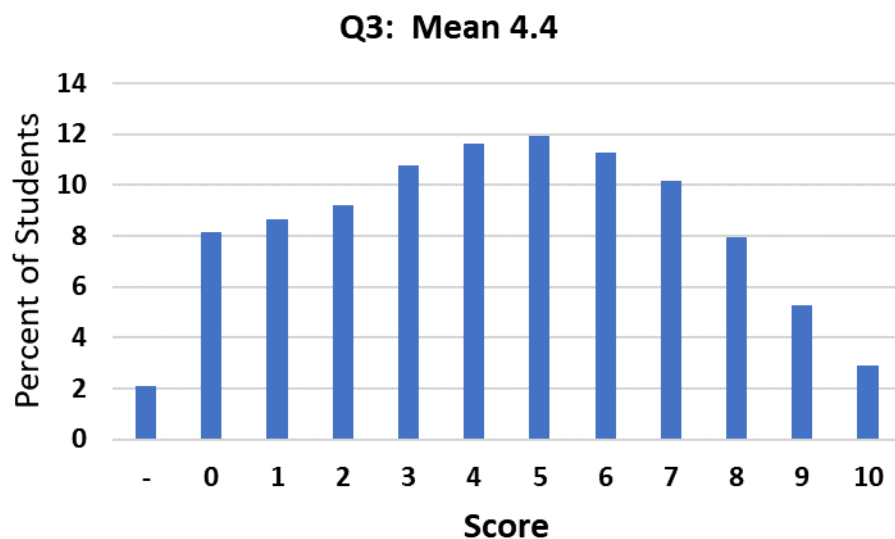
Part (a) was challenging for many students because it required them to identify the precipitate and assign ionic charges correctly. Responses often indicated $Cu(NO_3)_2$ as the product, had incorrect or missing electronic charges on the reactants or products, or failed to balance the equation with respect to mass and/or charge. By contrast, students did well determining the mass of the precipitate in part (b). This part was worth two points; the second point required the student to convert the mass of precipitate to moles of precipitate and report their answer to the correct number of significant figures. This point was frequently missed due to incorrect rounding. In part (c), many responses attempted to calculate the molarity of the original

$CuSO_4$ solution based upon the amount of excess reagent, $Ba(NO_3)_2(aq)$, rather than upon the amount of $BaSO_4$ precipitate. The volume of the original $CuSO_4$ solution was often indicated incorrectly as 500 mL, 70 mL, or 20 mL.

Most students successfully set up the dilution formula in part (d) but not all performed the algebraic rearrangement correctly. The procedure for preparing the dilute sample of $CuSO_4$, in part (e), was one of the hardest parts of Question 3. Many responses mentioned inappropriate equipment and/or procedures for measuring the volume of the stock solution and the volume of the final diluted sample. The standard curve in part (f) was interpreted correctly by most students and was one of the most frequently earned points. In part (g), many students correctly concluded that the residual water in the cuvette would cause the measured concentration to be less than the actual concentration, although they sometimes struggled to construct a cogent explanation for why.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
Part (a): • Misidentifying the precipitate, often as $Cu(NO_3)_2$ or $Ba(SO_4)_2$ • Omitting or mis-assigning ionic charge to species (sulfate was frequently assigned a charge of -1) • Writing an equation that was unbalanced with respect to mass and/or charge	$Ba^{2+}(aq) + SO_4^{2-}(aq) \rightarrow BaSO_4(s)$
Part (b): • Using 1.136 g (the mass of the filter paper and dried precipitate) as the mass of the precipitate • Reporting the number of moles of $BaSO_4$ with an incorrect number of significant figures	$1.136 \text{ g} - 0.764 \text{ g} = 0.372 \text{ g } BaSO_4$ $0.372 \text{ g} \times \frac{1 \text{ mol } BaSO_4}{233.39 \text{ g } BaSO_4} = 0.00159 \text{ mol } BaSO_4$
Part (c): • Using the concentration and volume of the aqueous $Ba(NO_3)_2$ solution to calculate moles of $CuSO_4$ • Dividing by total volume of the mixture (0.0700 L) instead of the original volume of the $CuSO_4$ solution (0.0500 L)	$0.00159 \text{ mol } BaSO_4 \times \frac{1 \text{ mol } CuSO_4}{1 \text{ mol } BaSO_4} = 0.00159 \text{ mol } CuSO_4$ $\frac{0.00159 \text{ mol } CuSO_4}{0.0500 \text{ L}} = 0.0318 \text{ M } CuSO_4$
Part (d): • Rearranging the dilution equation incorrectly	$M_1 V_1 = M_2 V_2$ $V_1 = \frac{(0.0500 \ M)(50.00 \text{ mL})}{(0.1000 \ M)} = 25.0 \text{ mL}$

Part (e):	First, measure out the correct volume of $0.1000\ M$ $CuSO_4$ solution with a 25.0 mL volumetric pipet (graduated cylinder or buret is acceptable)
• Using incorrect equipment for measuring and diluting the $0.1000M$ $CuSO_4$ solution, or not mentioning equipment at all • Filling a 50.00 mL volumetric flask "halfway full" or "up to the 25.00 mL mark" with $0.1000M$ $CuSO_4$ solution • Reversing the order of addition, i.e., adding 25.00 mL of distilled water to the volumetric flask and then filling up to the mark with $0.1000\ M$ $CuSO_4$ solution	Transfer the 25.0 mL of solution to a 50.00 mL volumetric flask and dilute the solution with water up to the 50.00 mL mark.

Part (f):	
• Calculating or estimating a number that is out of range or has the incorrect order of magnitude (often $0.35\ M$)	• $y = mx = \dfrac{0.63}{0.1000}x = 6.3x$ $x = \dfrac{y}{6.3} = \dfrac{0.219\ M}{6.3} = 0.035\ M$ or • Estimated value from the graph within the specified range ($0.032\ M - 0.038\ M$)

Part (g):	
• Stating that the residual water will increase, or have no influence on, the measured absorption (concentration) • Attributing the lower measured absorption (concentration) to a chemical reaction between $CuSO_4$ and water	The concentration will be <u>less than</u> that determined in part (f). The additional water will decrease the concentration of $CuSO_4$ in the cuvette. Therefore, there will be a decrease in absorbance (according to the Beer-Lambert law). This dilution results in a lower estimated concentration of $CuSO_4$.

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

1. Emphasize the importance of balancing chemical equations for both mass and charge. Illustrate the differences between net ionic and other types of chemical equations.
2. Review the electronic charges of common ions, particularly polyatomic species such as sulfate ion.
3. Practice applying solubility rules to predict the identity of a precipitate.
4. Provide opportunities for students to prepare solutions for laboratory experiments using proper equipment and methods.
5. Perform gravimetric analysis and spectrophotometric experiments for determining the concentrations of ions in solutions.
6. After each laboratory experiment, consider possible experimental errors and provide questions where students use claim, evidence, and reasoning to indicate the effect that the errors have on the experiment.
7. Model for students by "thinking aloud" the process of identifying errors and predicting their effect on experimental results.

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

- Teachers can use AP Classroom to direct students to the AP Daily videos on Topics on 3.7, 3.13, 4.2, and 4.5.
- Teachers can use AP Classroom to direct students to Review Session 6: Experimental Methods & Analysis of Free-Response Questions.
- Teachers can use online simulators like [ChemCollective—Qualitative and Quantitative Analysis of Food Dye](#) and [PhET—Beer's Law Lab](#) to build student skill and understanding prior to conducting an experiment similar to Investigations 1 and 2 in the *AP Chemistry Guided Inquiry Experiments* (available in Course-level Resources in AP Classroom). Teachers can also engage students in building their own spectrophotometer using a Smartphone using the information in [this article on ChemEd X](#).
- Teachers can use a variety of gravimetric analysis labs, such as [Investigation 3—What Makes Hard Water Hard?](#) from the lab book, *AP Chemistry Guided Inquiry Experiments*.
- Teachers can assign topic questions and/or personal progress checks in AP Classroom to monitor student progress and identify areas for additional instruction or content and skill development.

Question #4 **Task:** Analysis of iron oxidation   **Topics:** Calorimetry, stoichiometry

Max. Points: 4   **Mean Score:** 1.22

What were the responses to this question expected to demonstrate?

Question 4 involves the catalytic oxidation of elemental iron inside a small container of sand to produce Fe_2O_3. Part (a) asks for a calculation of the heat absorbed by the iron/catalyst/sand mixture given the change in temperature of the system (ENE-2.D, 5.F). In part (b), the student must calculate the mass of iron required to generate the amount of heat produced in the previous part. Two points are possible for this part: one for determining the number of moles of reaction (ENE-2.F, 5.F) and one for the calculated mass of iron (SPQ-1.A, 5.F). Part (c) asks the student to predict how the maximum temperature would change, if at all, if the quantity of iron were doubled (ENE-2.D, 2.F).

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

The mean score for Question 4 was 1.2 out of a possible four points, with a standard deviation of 1.3 points. The distribution of scores on this question is shown below.

Q4: Mean 1.2
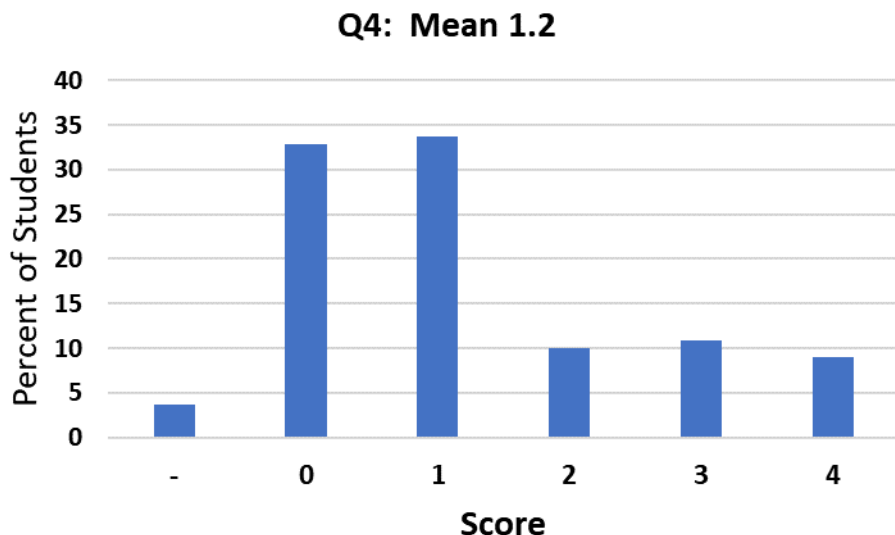
Part (a) was the most accessible point, demonstrating a widespread proficiency with the thermochemical equation $q = mc\Delta T$. In a few cases, the response used a temperature change based upon some time interval other than the 0–4 minutes indicated in the prompt. Occasionally, the point was not earned due to a missing or incorrect unit in the final answer.

Very few responses earned full credit for part (b). Although most reported a positive mass of iron, very few explicitly showed the inversion of mathematical sign with the relationship $q_{sys} = -q_{surr}$. Very often the student neglected to account for the stoichiometry of the reaction, indicating incorrectly that 1650 kJ was released when <u>one</u> mole of Fe(s) reacts. Others struggled with conversions between units of joules and kilojoules. A few responses bypassed thermochemical thinking altogether and assumed that the reaction produced 15.0 grams of Fe_2O_3 because the mass of the iron/catalyst/sand mixture was 15.0 grams.

The point in part (c) was rarely earned. Responses generally recognized that the temperature would be higher but stumbled when providing the justification. Some simply restated the prompt ("more iron is present") while others used incorrect reasoning related to thermodynamics, kinetics, or equilibrium. Other responses used a $q = mc\Delta T$ approach which, while valid, was often executed incorrectly. Students who earned the point clearly explained that with an increase in the amount of iron, the reaction released a greater amount of energy, resulting in a greater maximum temperature.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
Part (a): • Reporting an answer with incorrect units (cal, J/g, °C) or no units at all • Reversing the mathematical sign of the answer without explanation, thereby reversing the meaning of the ΔT term	$q = mc\Delta T$ $q = (15.0\text{ g})(0.72\text{ J}/(\text{g} \cdot {}^\circ\text{C}))(39.7\,{}^\circ\text{C} - 22.0\,{}^\circ\text{C}) = 190\text{ J}$
Part (b): • Failing to account for the change in mathematical sign between heat absorbed in part (a) and the heat released by the reaction • Mistaking the mass of the starting mixture (15.0 g of Fe(s), SiO_2, and catalyst) for the mass of Fe_2O_3 that was produced in the reaction • Converting between joules and kilojoules incorrectly (often 1000 kJ = 1 J) or not at all • Missing the stoichiometric conversion of 1650 kJ of energy being released when <u>four</u> moles of Fe(s) react	$q_{sys} = -q_{surr}$ $-190\text{ J} \times \dfrac{1\text{ kJ}}{1000\text{ J}} \times \dfrac{1\text{ mol}_{rxn}}{-1650\text{ kJ}} = 0.00012\text{ mol}_{rxn}$ $0.00012\text{ mol}_{rxn} \times \dfrac{4\text{ mol Fe}}{1\text{ mol}_{rxn}} \times \dfrac{55.85\text{ g Fe}}{1\text{ mol Fe}} = 0.027\text{ g Fe}$
Part (c): • Invoking unrelated concepts such as kinetic molecular theory or Le Chatelier's principle • Claiming that the additional Fe(s) absorbs heat or acts as a thermal conductor that dissipates heat to the surroundings • Stating that the temperature decreases because the equation $q=mc\Delta T$ states that mass and temperature are inversely proportional	Greater than. A greater mass of iron provides a greater number of moles of reaction, which would transfer a greater quantity of thermal energy to the same mass of sand and, therefore, lead to a greater maximum temperature.

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

1. Show students the benefits of using dimensional analysis in intermediate work so that they can avoid simple errors like expressing heat in units of J/°C or °C. Review the common errors (1 J = 1000 kJ) in conversions between units.
2. Reinforce the mathematical expression for the conservation of thermal energy ($q_{sys} = -q_{surr}$) to avoid errors of mathematical sign.
3. Demonstrate how the stoichiometric coefficients for each species in a balanced chemical reaction are related to the overall ΔH_{rxn}.
4. Practice identifying the key chemical concepts involved in an experiment (calorimetry and conservation of energy, versus kinetics or equilibrium).
5. Encourage students to use precise vocabulary in their explanations. Terms like kinetic energy, thermal energy, and temperature are related but not exactly the same.

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

- Teachers can use AP Classroom to direct students to the AP Daily videos on Topics 6.4 and 6.6.
- Teachers can review the Units in Thermochemical Calculations in the Classroom Resources section of AP Central for tips on how to use the mole of reaction to help students understand how to use coefficients in chemical equations with thermochemical quantities like $\Delta H_{rxn.}$
- Teachers can assign topic questions and/or personal progress checks in AP Classroom to monitor student progress and identify areas for additional instruction or content and skill development.

Question #5   Task: Analysis of an electrolytic cell   **Topics:** Electrochemistry

Max. Points: 4   **Mean Score:** 1.12

What were the responses to this question expected to demonstrate?

Question 5 provides a diagram of an electrolytic cell in which $MgCl_2$ is decomposed into its constituent elements. In part (a), the student must draw an arrow to indicate the direction of electron flow in the cell (ENE-6.A, 3.B). Part (b) asks whether a driving voltage of 2.0 V would be sufficient for the reaction to occur and to provide supporting quantitative evidence (ENE-6.B, 6.D). In part (c), the student calculates the amount of time required for the cell to produce a given mass of elemental magnesium. The question is worth two points: one for identifying the number of moles of electrons involved in the process (SPQ-1.A, 5.F) and one for correctly calculating the number of seconds (ENE-6.D, 5.F).
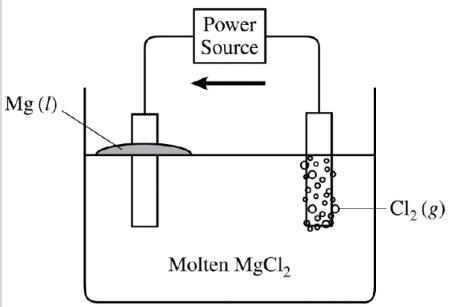
How well did the responses address the course content related to this question? How well did the responses integrate the skills required on this question?

The mean score for Question 5 was 1.1 out of a possible four points, with a standard deviation of 1.3 points. The distribution of scores on this question is shown below. Most students attempted to answer at least some parts of Question 5.

Q5: Mean 1.1
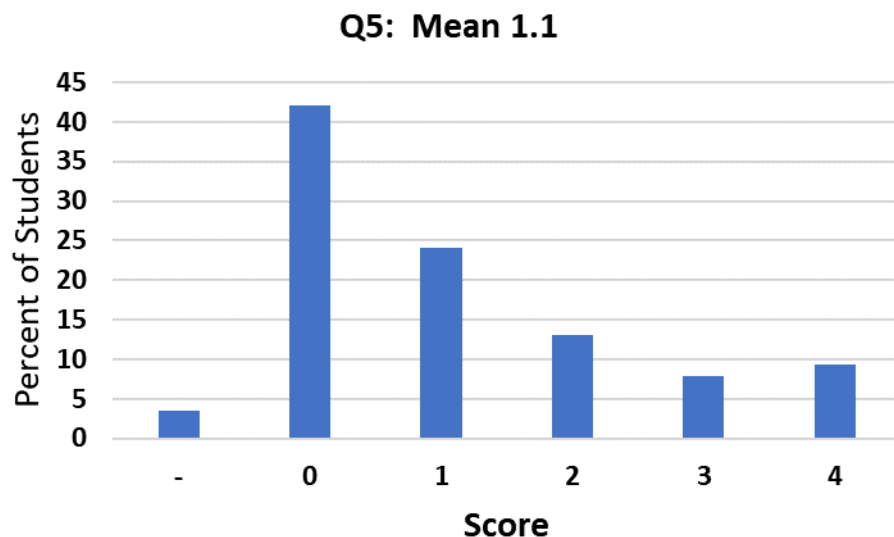
The arrow in part (a) was the most frequently earned point. Common errors included an arrow in the reverse direction (from the Mg cathode to the Cl_2 anode) or an arrow passing through the molten $MgCl_2$ rather than through the external circuit. Students struggled in part (b), primarily with sign conventions (reporting $E°_{cell}$ = +3.73 V rather than −3.73 V). Many responses failed to earn the point because they did not show any work for the calculation. Others provided a valid calculation but misinterpreted its meaning, stating that "yes," an applied voltage of 2.0 V would be sufficient to drive the electrolysis. Many responses to part (c) started with the equation $I = q/t$ and then suddenly stopped, implying that students could select an appropriate mathematical expression but grappled with how to apply it. Some students successfully calculated the number of moles of electrons involved in the process and earned the first point, but only earned the second point if they recognized an ampere as a Coulomb per second and Faraday's constant as a conversion between moles of electrons and total charge. The best answers used dimensional analysis clearly and effectively.

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

Common Misconceptions/Knowledge Gaps	Responses that Demonstrate Understanding
Part (a): • Drawing an arrow in a clockwise direction (treating the cell as voltaic rather than electrolytic) • Drawing an arrow that passed through the molten $MgCl_2$	Electron flow in a counter-clockwise direction in the external circuit, from the Cl_2 anode to the Mg cathode
Part (b): • Reversing the mathematical sign of the standard cell potential, reporting it as $+3.73$ V rather than -3.73 V • Incorrectly comparing the values of the applied voltage and $E°_{cell}$, e.g., "Yes, because 2.0 V is greater than -3.73 V" • Performing the calculation without any supporting work	No, because 2.0 V is less than 3.73 V, which is the minimum voltage needed for electrolysis to occur. $E°_{cell} = -2.37 \text{ V} + (-1.36 \text{ V}) = -3.73 \text{ V}$

Part (c):
 	
• Missing the stoichiometric conversion implying that two moles of electrons are required to reduce one mole of magnesium ions to elemental magnesium
 	
• Missing or misapplying essential conversion factors:
 	
   o Faraday's constant converts between moles of electrons and total charge.
 	
   o An ampere is a unit of current, i.e., Coulombs per second.
 	
• Performing the calculation without any supporting work
	$2.00 \text{ g Mg} \times \dfrac{1 \text{ mol Mg}}{24.30 \text{ g Mg}} \times \dfrac{2 \text{ mol } e^-}{1 \text{ mol Mg}} = 0.165 \text{ mol } e^-$
	
	$0.165 \text{ mol } e^- \times \dfrac{96,485 \text{ C}}{1 \text{ mol } e^-} \times \dfrac{1 \text{ s}}{5.00 \text{ C}} = 3180 \text{ s}$

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

1. Compare voltaic and electrolytic cells and the means by which to identify the type of cell represented in a diagram.
2. Ask students to describe the operation of electrochemical cells in terms of electron flow, half-reactions, and standard cell potential. Have them identify the anode and cathode according to the materials being oxidized and reduced.
3. Emphasize the meaning of mathematical sign in half-reactions and standard cell potential as they relate to the thermodynamic favorability of electrochemical processes.
4. Use dimensional analysis to practice using Faraday's law of electrolysis: converting between mass of reactant, moles of electrons involved in the process, electrical charge per mole of electrons, electrical current, and time.
5. Implement electrochemistry experiments into classroom demonstrations or the laboratory curriculum to illustrate these key concepts.

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

- Teachers can use AP Classroom to direct students to the AP Daily videos on Topics 9.8 and 9.10.
- Teachers can use the interactive Electrolysis Computer Simulation and the accompanying Student Activity to visualize the atomic-level processes in an electrolytic cell, practice net-ionic reaction writing, and calculate various quantities using Faraday's law.
- Teachers can assign topic questions and/or personal progress checks in AP Classroom to monitor student progress and identify areas for additional instruction or content and skill development.

Question #6 **Task:** Analysis of sulfate salts   **Topics:** Properties of ionic compounds, solubility equilibria

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

What were the responses to this question expected to demonstrate?

Question 6 focuses upon two salts, $CaSO_4$ and $PbSO_4$. In part (a), the student must explain why neither compound conducts electricity in its solid state (SAP-5.B, 1.B). The student is then presented with electrical conductivity data on saturated solutions of each salt and asked to identify which compound is more soluble in water and to explain why (SAB-5.B, 2.D). A particulate representation of the saturated solution of $CaSO_4$ is provided, and a corresponding diagram of the $PbSO_4$ solution must be drawn that is consistent with the relative solubility of the two salts (SPQ-5.A, 3.C). Finally, in part (d), the student explains why adding sulfuric acid to the saturated solution of $CaSO_4$ produces additional precipitate (SPQ-5.B, 6.F).

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

The mean score for Question 6 was 1.3 out of a possible four points, with a standard deviation of 1.2 points. The distribution of scores on this question is shown below. Question 6 had the highest average among the four short (4–point) free response questions.
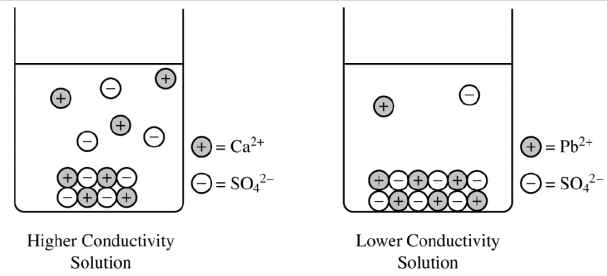

Q6: Mean 1.3
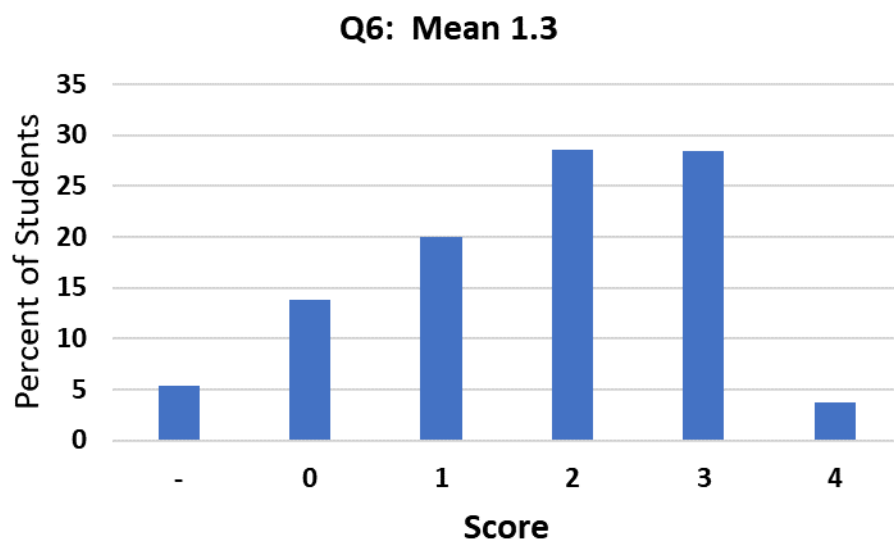
Most responses to part (a) reflected an understanding of electrical conductivity, although some tried to frame the observation entirely in terms of whether or not the bonding within a solid may be represented by the "sea of electrons" model. Students who incorrectly invoked the mobility of electrons in solids in part (a) often correctly argued about the mobility of ions in solution in other parts of the question. Part (b) was accessible for most students. However, many simply stated that greater conductivity is equivalent to greater solubility, without any form of reasoning or further explanation. To earn credit, it was necessary to attribute the higher conductivity of the saturated $CaSO_4$ solution to a greater concentration of ions in solution (greater extent of dissociation).

Part (c) was the most frequently earned point. Students generally seemed comfortable with the particulate representation and its relationship to the solubility of each material and the degree of electrical conductivity of the resulting saturated solutions. Students who gave an incorrect answer to part (b) could earn credit here if they provided a diagram that was consistent with their earlier answer.

In part (d), a common answer was that "There is more SO_4^{2-} available to react," without any further explanation. Since this fact is already reflected in the prompt, the student had to provide additional reasoning based upon chemical equilibrium (common ion effect, Le Chatelier's principle, comparison of Q vs. K_{sp}) 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
Part (a): • Focusing entirely on the mobility of electrons, rather than ions, as the cause of electrical conductivity • Misattributing the lack of conductivity to the type of bonding within each solid (i.e., the salts cannot be described by the "sea of electrons" model)	Ionic solids do not have free-flowing ions that are required to carry an electric current. Therefore, there is no conduction of electricity.
Part (b): • Asserting a claim without further explanation: "Higher conductivity equals higher solubility." • Failing to attribute the degree of conductivity to the concentration of ions	$CaSO_4$. The greater electrical conductivity of the $CaSO_4$ solution relative to the $PbSO_4$ solution implies a higher concentration of ions, which comes from the dissolution (dissociation) of $CaSO_4$ to a greater extent.
Part (c): • Showing an inequal number of cations and anions in solution and/or the solid • Drawing the same representation as the beaker on the left	Solid $PbSO_4$ at the bottom of the beaker and fewer dissociated Pb^{2+} and SO_4^{2-} ions in solution
Part (d) : • Failing to describe the system in terms of chemical equilibrium, i.e., stating only that SO_4^{2-} reacts with Ca^{2+}, as if the process was a simple precipitation reaction	The additional precipitate is $CaSO_4$ that forms in response to the increased $[SO_4^{2-}]$ in solution. According to Le Chatelier's principle ($Q>K_{sp}$), the introduction of SO_4^{2-} as a common ion shifts the equilibrium toward the formation of more $CaSO_4(s)$.

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

1. Teach students that a complete explanation must include evidence and reasoning, not just repeating the prompt or reciting a trend. Have students practice their reasoning skills in both speaking and writing.
2. Incorporate particle-level drawings to describe chemical phenomena.
3. Highlight the similarities and differences between electrical conductivity in metals (electron sea) and dissolved or molten salts (mobile ions).
4. Encourage students to be specific and precise in their verbal answers. "Sulfate is the common ion" is better than "there is a common ion" or "it is a common ion."

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

- Teachers can use AP Classroom to direct students to the AP Daily videos on Topics 3.2, 7.11, and 7.12.
- Teachers can use the PhET simulation—Salts & Solubility—and several accompanying Teacher-Submitted Activities to connect particle-level views to calculations of solubility and K_{sp}.
- Teachers can assign topic questions and/or personal progress checks in AP Classroom to monitor student progress and identify areas for additional instruction or content and skill development.

Question #7   Task: Analysis of O_2 gas

Topics: Density, kinetic molecular theory, intermolecular forces

Max. Points: 4

Mean Score: 1.01

What were the responses to this question expected to demonstrate?

Question 7 involves a sample of O_2 inside a container with a movable piston. In part (a), the student must calculate the density of the gas based upon its mass and volume (SPQ-1.A, 5.F). Part (b) asks whether releasing some of the gas from the container will change the density of the gas, and to justify the answer (SAP-7.A, 2.B). The volume of the gas decreases upon cooling, and part (c) asks the student to explain this observation in terms of kinetic molecular theory (SAP-6.A, 4.C). Part (d) requires an explanation for why the measured volume of O_2 gas deviates from that predicted by the ideal gas law at low temperature (SAP7.C, 4.C).

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

The mean score for Question 7 was 1.0 out of a possible four points, with a standard deviation of 0.9 point. The distribution of scores on this question is shown below. Although most students attempted this question, it was the lowest scoring out of all the free-response questions on the exam.

Q7: Mean 1.0
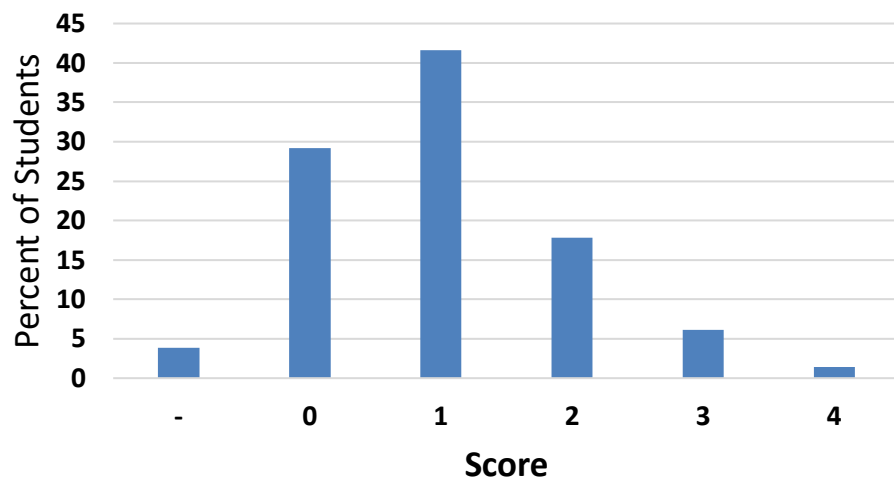
Part (a) was the most accessible part of Question 7. The successful students used dimensional analysis to convert moles of O_2 to grams of O_2 and then calculate the density of the gas. A surprising number of responses used the ideal gas equation to calculate the number of moles of O_2, even though this information was already provided in the prompt, and sometimes calculated the number of moles of O_2 incorrectly. Others ignored the information in the prompt and declared that the cylinder contained exactly 32.0 g (1.00 mole) of O_2.

Nearly every student answered part (b), but only about half earned the point. Many responses used Boyle's law, perhaps overlooking the open valve on the side of the cylinder. Others focused entirely on the mass of O_2 being lower, without mentioning the proportional reduction in the volume of gas. Statements about the temperature and/or pressure of the gas remaining constant were insufficient; the concept of proportionality was required to earn credit.

Most students attempted part (c) but did not earn credit. Responses often bypassed the requirement of using kinetic molecular theory and instead used only the ideal gas law or Charles' law. For those who correctly correlated a lower temperature with a lower average kinetic energy of particles, many times the explanation for why the volume of the gas decreased was incorrect or missing. Some students argued that the gas particles themselves decreased in volume.

About half of students attempted part (d), and only about one-third of those earned credit. Many argued incorrectly that the entire sample of O_2 gas had condensed into a liquid or solid. Responses had to explain the relationship between nonideal gas behavior, interparticle forces, and the resulting effect on the volume of the gas.

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

Common Misconceptions/Knowledge Gaps	*Responses that Demonstrate Understanding*
Part (a): • Using the molar mass of O_2 (32.0 g/mol) as the mass of gas inside the cylinder • Expressing density as moles per liter • Calculating (incorrectly) the number of moles of O_2 by using the ideal gas equation	• $0.325 \text{ mol } O_2 \times \dfrac{32.00 \text{ g } O_2}{1 \text{ mol } O_2} = 10.4 \text{ g } O_2$ $D = \dfrac{m}{V} = \dfrac{10.4 \text{ g}}{7.95 \text{ L}} = 1.31 \text{ g/L}$ or • $D = \dfrac{m}{V} = \dfrac{P(MM)}{RT} = \dfrac{(1.0 \text{ atm})(32.00 \text{ g/mol})}{(0.08206 \frac{\text{L·atm}}{\text{mol·K}})(298 \text{ K})} = 1.31 \text{ g/L}$
Part (b): • Overlooking the open valve on the cylinder, which allows some gas to escape • Neglecting to mention that the mass of O_2 and the volume of O_2 decrease <u>proportionately</u> • Stating only that temperature and/or pressure remains constant, without discussing the density of the gas	• No, the density of the gas remains constant because P, R, and T remain constant AND the mass and volume of O_2 decrease proportionately or • $D = \dfrac{m}{V} = \dfrac{n \text{ moles of } O_2 \times \text{molar mass of } O_2}{\dfrac{nRT}{P}} = \dfrac{P(MM)}{RT}$
Part (c): • Failing to use principles of kinetic molecular theory (often just Charles's law or the ideal gas law) • Stating that the gas particles decrease in size or become immobilized	• As the gas cools, the average kinetic energy (speed) of the O_2 molecules decreases. The molecules rebound with less energy when they collide with each other and the walls of the container. The spacing between particles decreases, causing the volume occupied by the gas to decrease. or • As the gas cools, the average kinetic energy (speed) of the O_2 molecules decreases. The molecules rebound with less energy when they collide with each other and the walls of the container. The only way for the molecules to maintain a constant rate of collisions with the walls of the container (maintaining a pressure of 1.00 atm) is for the volume of the gas to decrease.

Part (d):	
• Describing O_2 at −180°C (above the boiling point of −183°C) as a liquid or solid • Implying that low temperature and/or intermolecular forces cause gas particles to become frozen in space	The ideal gas law assumes that gas particles do not experience interparticle attractions. As a real gas cools further, the intermolecular forces have greater effect as the average speed of the molecules decreases, resulting in inelastic collisions. To maintain a gas pressure of 1.00 atm, the volume must decrease to accommodate more collisions with less energy.

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

1. Emphasize that particles of gas will completely fill their container and that both the force and frequency of the collisions of the particles on the walls of the container contribute to the pressure of the gas. If the gas is inside a flexible container, the volume of the container will expand or shrink to maintain a balance between the internal pressure of the gas and external pressure on the outside of the container.
2. Ask students to predict the physical state of a substance at a given temperature, especially at temperatures below 0°C that require comparing the relative magnitude of two negative numbers.
3. Describe the behavior of ideal gases and real gases in terms of kinetic molecular theory. Many responses to Question 7 tried to use Boyle's law and Charles's law quantitatively, rather than using qualitative principles of particle motion.
4. Use computer animations to illustrate the behavior of gas particles under a variety of conditions: changing temperature, changing pressure, and phase changes.
5. Explicitly connect real gas behavior to the types and relative strengths of intermolecular forces among the particles.

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

- Teachers can use AP Classroom to direct students to the AP Daily videos on Topics 3.3, 3.4, and 3.5.
- Teachers can use the videos and live discussions at APTeach.org (Intermolecular Forces, Intermolecular Forces—Instructional Sequence, and Hydrogen Bonding).
- Teachers can use online simulators like PhET—Gas Properties, AACT—Gas Laws Simulation, sim bucket—The Behavior of Gases, and Molecular Workbench—States of Matter can be used to develop student models for gas behavior under a variety of conditions, which can then be explained with Kinetic Molecular Theory.
- Teachers can assign topic questions and/or personal progress checks in AP Classroom to monitor student progress and identify areas for additional instruction or content and skill development.