



Chief Reader Report on Student Responses: 2025 AP[®] Chemistry Free-Response Questions

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|-----------------------------|------------|--------|------|
| • Number of Students Scored | 170,283 | | |
| • Number of Readers | 713 | | |
| • Score Distribution | Exam Score | N | %At |
| | 5 | 30,277 | 17.8 |
| | 4 | 48,732 | 28.6 |
| | 3 | 53,601 | 31.5 |
| | 2 | 27,116 | 15.9 |
| | 1 | 10,557 | 6.2 |
| • Global Mean | 3.36 | | |

The following comments on the 2025 free-response questions for AP[®] Chemistry were written by the Chief Reader, Kyle A. Beran, Angelo State University. They give an overview of each free-response question and of how students performed on the question, including typical student errors. General comments regarding the skills and content that students frequently have the most problems with are included. Some suggestions for improving student preparation in these areas are also provided. Teachers are encouraged to attend a College Board workshop to learn strategies for improving student performance in specific areas.

Question 1

Task: Mg Mass Spectrum and Hydroxide Solubility

Topic: Mass Spectrum, Interparticle Forces, pH of Strong Bases, Solutions, Reaction Quotient and Equilibrium Constant, Solubility Equilibria, pH and Solubility

| | Max Points: | Mean Score: |
|--------------------------|-------------|-------------|
| Point 01 | 1.0 | 0.72 |
| Point 02 | 1.0 | 0.55 |
| Point 03 | 1.0 | 0.65 |
| Point 04 | 1.0 | 0.11 |
| Point 05 | 1.0 | 0.66 |
| Point 06 | 1.0 | 0.46 |
| Point 07 | 1.0 | 0.59 |
| Point 08 | 1.0 | 0.42 |
| Point 09 | 1.0 | 0.45 |
| Point 10 | 1.0 | 0.17 |
| Overall Mean Score: 4.78 | | |

What were the responses to this question expected to demonstrate?

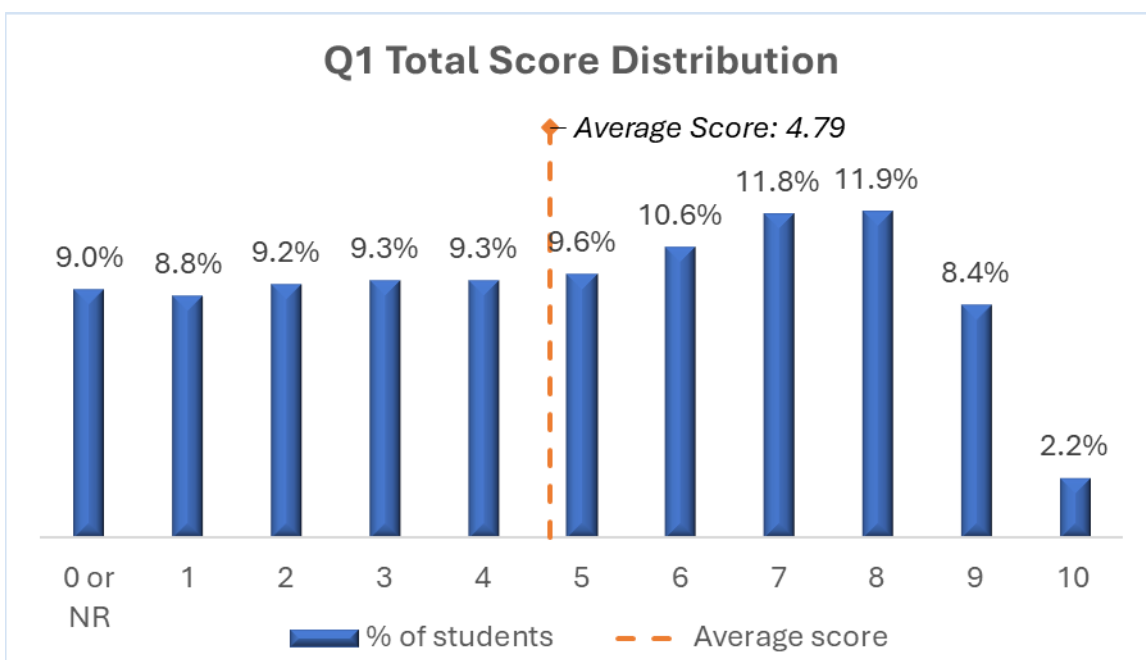
Question 1 presents students with a series of questions involving magnesium hydroxide, including the mass spectrum of magnesium, the relative strength of hydration of magnesium ions, and the solubility of magnesium hydroxide.

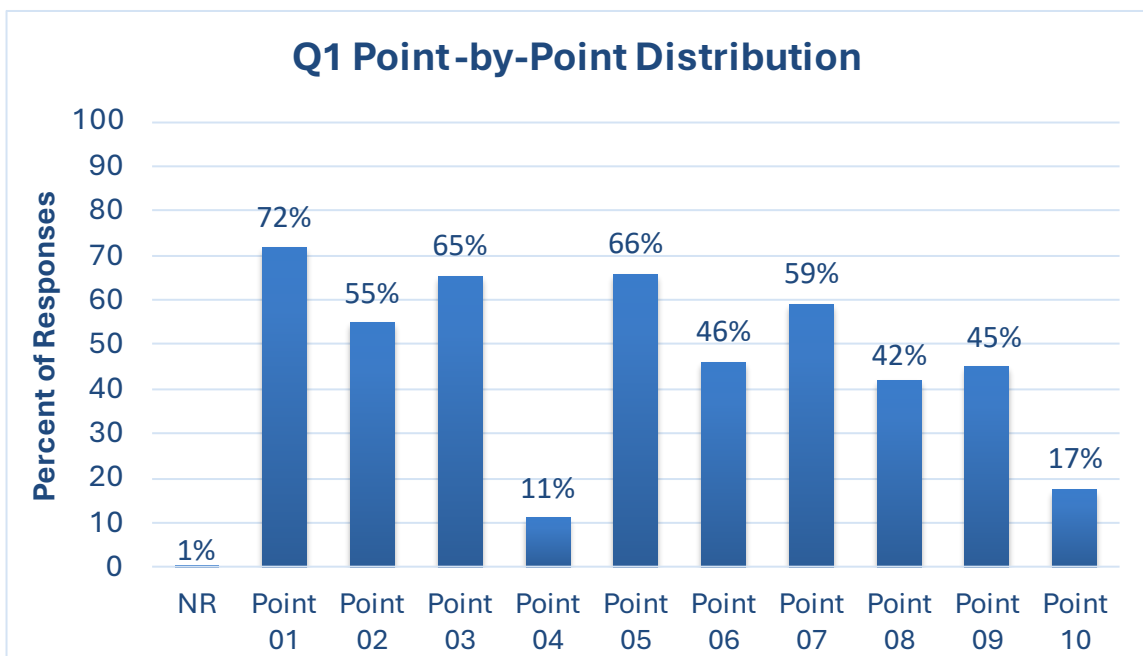
- Part A (i) requires students to annotate an incomplete mass spectrum with lines for two isotopes of magnesium of approximately equal percent abundances. The intent was for students to recognize that the total relative abundance in a mass spectrum must add up to 100. (Learning Objective 1.2.A and Skill 3.A from the *AP Chemistry Course and Exam Description*)
- Part A (ii) requires students to identify the difference in atomic structure that causes isotopes to have different masses. The intent was for students to state that different isotopes of the same element have different numbers of neutrons. (1.2.A; 6.A)
- Part B requires students to explain, using Coulomb's law, why sodium ions are less strongly attracted to water molecules in aqueous solution than magnesium ions. This explanation was divided into two parts: B (i) the relative attraction with water due to the charges of the two ions and (ii) the relative attraction with water due to the ionic radii of the two ions. The intent for B (i) was for students to recognize that a cation of lesser charge would form a weaker attraction to the partial negative oxygen in water. For part B (ii) the intent was for students to determine that a sodium ion would have a larger ionic radius than a magnesium ion and that an ion of larger ionic radius would have a greater degree of separation from the water molecule, resulting in a weaker attraction than a magnesium ion to water. (3.1.A; 4.C)
- Part C requires students to calculate the pH of an aqueous strong base solution. The intent was for students to recognize that sodium hydroxide fully ionizes in solution and that the pH of the solution can be calculated from the hydroxide concentration. (8.2.A; 5.F)
- Part D requires students to calculate the diluted concentration of magnesium ions in an aqueous magnesium hydroxide solution. The intent was for students to recognize that the original number of moles of Mg^{2+} remains constant and must be divided by the total volume of the diluted solution to calculate the correct concentration of magnesium ions. (3.7.A; 5.F)

- Part E is a series of questions that relate to whether a mixture of solutions containing magnesium ions and hydroxide ions will form a precipitate.
- Part E (i) provides the balanced equation for the reversible dissolution of magnesium hydroxide and requires that students write the K_{sp} equilibrium expression for this process. The intent was for students to recognize that only the aqueous species are to be reflected in the equilibrium expression and not the magnesium hydroxide solid. (7.3.A; 5.B)
- Part E (ii) requires students to calculate the value of the reaction quotient, Q , after the mixing of the two solutions but prior to any reaction. In addition to knowing how to calculate the reaction quotient for this mixture, the intent was for students to recognize that the calculated answer from part D, the diluted magnesium ion concentration, was to be used in this calculation, as well as the hydroxide ion concentration provided in the prompt. (7.3.A; 5.F)
- Part E (iii) requires students to determine if a precipitate will form as the mixture approaches equilibrium. The intent was for students to compare the calculated value for Q in part E (ii) to the numerical value of the K_{sp} that was provided in the prompt, and to use the results of that comparison to determine if a precipitate of magnesium hydroxide will form. (7.11.A; 2.B)
- Part F requires students to determine if the solubility of magnesium hydroxide is affected by the addition of strong acid. The intent of the question is for students to recognize that the reaction quotient, Q , will decrease because the acid will reduce the concentration of the aqueous hydroxide ions in solution, thereby decreasing the value of Q such that $Q < K_{sp}$ and resulting in a decrease in the amount of solid magnesium hydroxide until equilibrium is reestablished. (8.11.A; 2.F)

How well did the responses address the course content related to this question? How well did the responses integrate the skill(s) required on this question?

The mean score for Question 1 was 4.79 out of a possible 10 points. The total score distribution and the point-by-point distribution on this question are shown in the following figures.





- Part A (i) was very accessible for most students. Correct responses reflected that the sum of the two relative abundances should be approximately 21 and that the lines should be approximately equal heights, as required by the prompt. Finally, the response needed to apply appropriate graphing techniques including noting the scaling of the y -axis when drawing the lines.
- Part A (ii) was also moderately accessible for students. Correct responses contained a scientific claim that the isotopes of the same element have different masses due to differing numbers of neutrons.
- Part B (i) was quite accessible for students. Correct responses were able to interpret a particulate-level representation and to use the charges of two different monatomic cations as a basis to rank the relative magnitude of the ion-dipole attractions to water.
- Part B (ii) was a very challenging point for students to earn. Correct responses identified which ion has a greater ionic radius and correctly correlated that ionic radius to the interparticle separation between a cation and a water molecule, and how that degree of separation affects the Coulombic attraction.
- Part C was quite accessible, as most responses correctly reflected that sodium hydroxide is a strong base and fully ionizes. Students were generally successful in calculating the pOH of the sodium hydroxide solution and continuing on to determine the pH of the solution based on the calculated pOH value.
- Part D was moderately accessible for students. Students who earned the point calculated the molarity of magnesium ions by dividing the moles of Mg^{2+} by the total liters of the solution after dilution.
- Part E (i) was quite accessible for students. Students who earned this point were able to write a valid K_{sp} equilibrium expression given the net ionic equation describing the reversible solubility of solid magnesium hydroxide.
- Part E (ii) was moderately accessible for students. Correct responses appropriately substituted the magnesium ion concentration calculated in part D and the given hydroxide concentration into the reaction quotient formula, and calculated the correct value for the reaction quotient, Q .

- Part E (iii) was also moderately accessible for students. Students who earned this point were able to make a valid comparison between the value for Q calculated in E (ii) to the given K_{sp} value. In addition, a correct response conveyed that a precipitate would form in cases where the reaction quotient of a mixture, Q , is greater than the K_{sp} .
- Part F was very challenging for students. Correct responses stated adding an acid to a saturated magnesium hydroxide solution would result in a decrease in the amount of undissolved $\text{Mg}(\text{OH})_2$. Additionally, students who earned the point went on to justify this by describing that the aqueous $[\text{OH}^-]$ in the products side of the equation would decrease due to the addition of acid, and that this would cause the equilibrium position to shift toward the products, according to Le Châtelier's principle.

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> |
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| <p>Part A (i) – Point 01</p> <ul style="list-style-type: none"> • Misinterpreting the prompt and drawing the two lines to match the relative abundance of the line already on the graph. • Misinterpreting the scale of the y-axis. Some responses appear to have interpreted the second line on the y-axis as 11 instead of 20, because lines that should have been 10.5 relative abundance were drawn to 15 relative abundance. | <p>Part A (i) – Point 01</p> <p>The best responses did one of the following:</p> <ul style="list-style-type: none"> • Drew one line ending at the 10 relative abundance grid line and the other ending a very small distance above that grid line • Drew both lines ending at a very small distance above the 10 relative abundance grid line |
| <p>Part A (ii) – Point 02</p> <ul style="list-style-type: none"> • Ascribing the difference in isotope masses to the number of electrons and/or protons in an atom. • Assigning an incorrect number of neutrons to the isotopes. For example, “Mg–26 has 26 neutrons, Mg–25 has 25 neutrons.” | <p>Part A (ii) – Point 02</p> <ul style="list-style-type: none"> • The mass of Mg–26 is greater than the mass of Mg–25 because Mg–26 has one more neutron than Mg–25. • The mass of Mg–26 is greater than the mass of Mg–25 because Mg–26 has one more neutron: Mg–26 has 14 neutrons and Mg–25 has 13 neutrons. |
| <p>Part B (i) – Point 03</p> <ul style="list-style-type: none"> • Failing to make any kind of comparison. Simply stating, “Because magnesium is +2 and sodium is +1” fails to explain why one ion is more strongly hydrated than the other. Even if the response goes on to say, “therefore sodium ions have a weaker attraction to water,” that does not add value to the response because that fact was already stated in the prompt. | <p>Part B (i) – Point 03</p> <ul style="list-style-type: none"> • Sodium ions have a lower charge than magnesium ions, so according to Coulomb's law, they form weaker attractions to water than magnesium ions. |

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| <p>Part B (ii) – Point 04</p> <ul style="list-style-type: none"> Stating or implying that the “r” in Coulomb’s law represents the radius of the ion instead of the interparticle separation between the ion and water. Similarly, ascribing the weaker attraction of sodium ions to water solely to the radius of the ion, and not to the effect that the radius has on the interparticle separation from water. | <p>Part B (ii) – Point 04</p> <ul style="list-style-type: none"> A sodium ion is larger than a magnesium ion, which results in a greater distance between the sodium ion and a water molecule. According to Coulomb’s law, this will result in the sodium ion having a weaker attraction to a water molecule. |
| <p>Part C – Point 05</p> <ul style="list-style-type: none"> Using the hydroxide ion concentration to calculate what is actually pOH, but stopping there and calling that answer pH. Converting the molarity of sodium hydroxide to moles, then calculating pOH and pH from the moles (instead of molarity) of hydroxide. | <p>Part C – Point 05</p> <ul style="list-style-type: none"> $\text{pOH} = -\log(2.80 \times 10^{-4}) = 3.553$ $\text{pH} = 14.000 - 3.553 = 10.447$ |
| <p>Part D – Point 06</p> <ul style="list-style-type: none"> Multiplying the original molarity of magnesium ions by the initial volume of the sodium hydroxide solution. $\frac{(1.85 \times 10^{-3} M)(0.05000 \text{ L})}{0.08500 \text{ L}}$ Dividing the moles of magnesium ions by the volume of the sodium hydroxide solution instead of the total solution volume. $\frac{(1.85 \times 10^{-3} M)(0.03500 \text{ L})}{0.05000 \text{ L}}$ | <p>Part D – Point 06</p> <p>Common computational pathways:</p> <ul style="list-style-type: none"> $\frac{(1.85 \times 10^{-3} M)(0.03500 \text{ L})}{0.08500 \text{ L}} = 7.62 \times 10^{-4} M \text{ Mg}^{2+}$ $\begin{aligned} \text{mol Mg}^{2+} &= (1.85 \times 10^{-3} M)(0.03500 \text{ L}) \\ &= 6.48 \times 10^{-5} \text{ mol Mg}^{2+} \\ M \text{ Mg}^{2+} &= \frac{6.475 \times 10^{-5} \text{ mol Mg}^{2+}}{0.08500 \text{ L}} \\ &= 7.62 \times 10^{-4} M \text{ Mg}^{2+} \end{aligned}$ $\frac{(1.85 \times 10^{-3} M)(35.00 \text{ mL})}{85.00 \text{ mL}} = 7.62 \times 10^{-4} M \text{ Mg}^{2+}$ |

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| <p>Part E (i) – Point 07</p> <ul style="list-style-type: none"> Including a term for the concentration of a solid: $K_{sp} = \frac{[\text{Mg}^{2+}][\text{OH}^-]}{[\text{Mg}(\text{OH})_2]}$ Multiplying the hydroxide concentration by 2: $K_{sp} = [\text{Mg}^{2+}][2 \text{OH}^-]^2$ Using parentheses instead of square brackets: $K_{sp} = (\text{Mg}^{2+})(\text{OH}^-)^2$ Omitting the ion charges: $K_{sp} = [\text{Mg}][\text{OH}]^2$ Omitting the square: $K_{sp} = [\text{Mg}^{2+}][\text{OH}^-]$ | <p>Part E (i) – Point 07</p> <ul style="list-style-type: none"> $K_{sp} = [\text{Mg}^{2+}][\text{OH}^-]^2$ |
| <p>Part E (ii) – Point 08</p> <ul style="list-style-type: none"> Using a magnesium ion concentration other than what was calculated in part D. Neglecting to square the hydroxide ion concentration. | <p>Part E (ii) – Point 08</p> <ul style="list-style-type: none"> $Q = (7.62 \times 10^{-4})(1.65 \times 10^{-4})^2 = 2.07 \times 10^{-11}$ |
| <p>Part E (iii) – Point 09</p> <ul style="list-style-type: none"> Misinterpreting whether the calculated value for Q was greater or smaller than K_{sp} (indicating that a value of 5.61×10^{-12} was greater than a value of 2.07×10^{-11}). Correctly stating the relationship of Q to K_{sp}, but interpreting that relationship backwards. (“Q is greater than K_{sp}, so no precipitate will form.”) | <p>Part E (iii) – Point 09</p> <ul style="list-style-type: none"> The value for Q, 2.07×10^{-11}, is greater than the value for K_{sp}, 5.61×10^{-12}, so a precipitate will form. |

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| <p>Part F – Point 10</p> <ul style="list-style-type: none"> Attributing the decrease in the amount of undissolved magnesium hydroxide to a direct reaction between the magnesium hydroxide and the added acid. Correctly stating that the added acid reacts with the hydroxide in solution but without a sufficient discussion of the resulting shift in the equilibrium position. (“More magnesium hydroxide will dissolve because the H^+ from HNO_3 will react with OH^- ions.”) | <p>Part F – Point 10</p> <ul style="list-style-type: none"> The H^+ ions from HNO_3 react with the OH^- ions in solution, decreasing the hydroxide ion concentration. Because hydroxide is a product of a reversible reaction, the decrease in concentration will cause the equilibrium position to shift toward the products, reducing the amount of undissolved $\text{Mg}(\text{OH})_2$. The H^+ from HNO_3 reacts with the OH^- in solution, decreasing the hydroxide ion concentration. This will cause Q to be less than K_{sp}, and the reaction will shift right to reestablish equilibrium. |
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Based on your experience at the AP[®] Reading with student responses, what advice would you offer teachers to help them improve student performance on the exam?

- Coulomb’s Law:** Make it clear to students that when Coulomb’s law is applied to the attractions between two species (ionic bonds, IMF attractions, nucleus and electron attractions, etc.), the “ r ” in the formula stands for the separation (distance) between those substances, not the “radius” of just one of the substances. This misconception was observed many times in part B (ii).
- pH and the Common Ion Effect:** Many students had trouble conveying the effect that adding an acid has on the solubility of a slightly soluble basic salt. The common ion effect is in play here, but instead of the addition of a common ion, part E involves the “removal” of a common ion. This is a case where just memorizing that “basic salts are more soluble in acidic solution than neutral solution” did not help the student earn this point. One suggestion is to include at least one example of this concept when students are practicing equilibrium position shifts when teaching Le Châtelier’s principle. Use an equation like $\text{Mg}(\text{OH})_2(s) \rightleftharpoons \text{Mg}^{2+}(aq) + 2 \text{OH}^-(aq)$ and ask students to predict the direction of shift when hydroxide is removed. Then ask them to predict the direction of shift when H^+ is added. This will probably confuse them at first, but it sets up a great teachable moment to show them how exactly one would go about “removing” hydroxide from solution.
- Graphing Skills:** Give students many opportunities to practice placing or reading ordered pairs on graphs, especially when the ordered pair does **not** fall on a grid line and requires estimating between grid lines.
- Calculating pH of Basic Solutions:** Provide a lot of examples calculating the pH of basic solutions. This repetition should help them avoid the common mistake of thinking that they have calculated pH when they have actually calculated pOH.
- Expressing Uncertainty for Calculated pH, pOH and pK_a Values:** Even though this skill was not assessed on this question this year, teach students how to appropriately represent the uncertainty in values such as these. The number of decimal places in the calculated value should be the same as the number of significant figures in the $[\text{H}^+]$, $[\text{OH}^-]$, or K_a value. For example, the pOH of a $2.75 \times 10^{-6} \text{ M OH}^-$ solution should be reported as 5.561 to correctly reflect the uncertainty of the pOH value.

- **Atomic Structure:** Be sure that students can clearly compare and contrast the numbers of subatomic particles in different atoms and/or ions. For example, a common mistake made by students is attributing the different masses of two isotopes of magnesium to differing numbers of protons and/or electrons.
- **Dilution Mathematics:** If students use the “ $M_1V_1 = M_2V_2$ ” method of solving dilution problems, emphasize that V_2 represents the total, diluted volume, not the volume of water added. Many students substituted 50.00 mL into V_2 in part D of Question 1.
- **Comparing Q to K :** It is a common mnemonic to orient Q , K , and the inequality sign in such a way that leads to the correct direction of shift for reversible reactions that are not yet at equilibrium. While this may work generally, it does not help students understand the chemical principles governing the direction of shift. If this is the technique your students tend to use, consider spending a few extra minutes in class discussing this concept in terms of what changes must occur to the current-condition values in the numerator and/or denominator for that quotient to eventually become equal to K .

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

- Teachers can use AP Classroom to direct students to the AP Daily videos and assign topic questions for Topics 1.2, 1.7, 2.2, 3.1, 3.7, 7.3, 7.9, 7.10, 7.11, and 8.11.
- Teachers can utilize the PhET simulations on [Coulomb’s Law](#) and [Salts and Solubility](#) to help students connect measurements that are determined at the macroscopic scale (force, K_{sp}) to the particulate level.
- To illustrate the pH sensitivity of a slightly soluble salt, teachers can demonstrate [neutralizing milk of magnesia with a strong acid](#) in the presence of universal indicator.

Question 2

Task: Ascorbic Acid

Topic: Moles, Stoichiometry, Elemental Composition, Acid-Base Titrations, Henderson-Hasselbalch Equation, Rate Law, Intermolecular Forces

| | Max Points: | Mean Score: |
|--------------------------|-------------|-------------|
| Point 01 | 1.0 | 0.84 |
| Point 02 | 1.0 | 0.32 |
| Point 03 | 1.0 | 0.31 |
| Point 04 | 1.0 | 0.35 |
| Point 05 | 1.0 | 0.56 |
| Point 06 | 1.0 | 0.28 |
| Point 07 | 1.0 | 0.51 |
| Point 08 | 1.0 | 0.64 |
| Point 09 | 1.0 | 0.33 |
| Point 10 | 1.0 | 0.15 |
| Overall Mean Score: 4.29 | | |

What were the responses to this question expected to demonstrate?

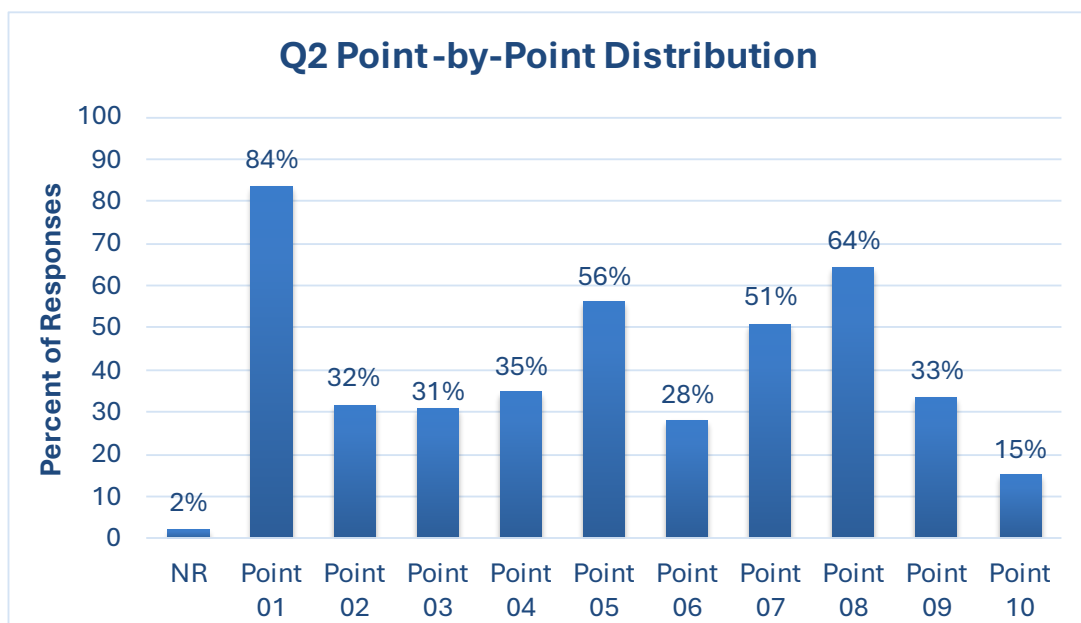
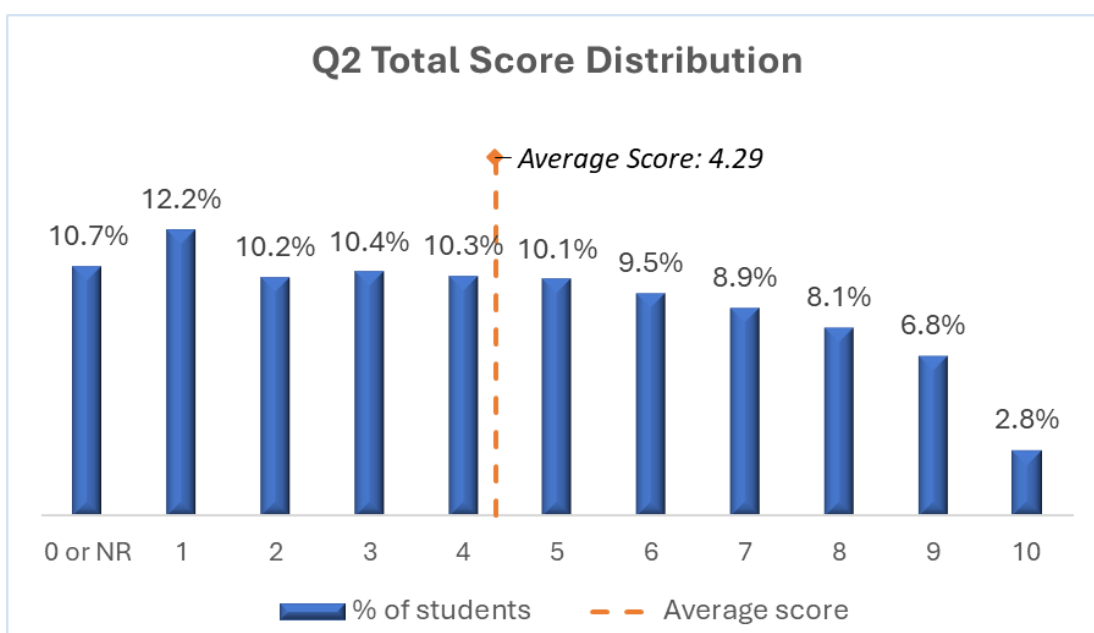
Question 2 presents students with a sequence of items regarding ascorbic acid (vitamin C).

- Part A (i) requires students to calculate the moles of H_2O from the mass of H_2O provided. The intent was for students to use a calculated molar mass of H_2O to then calculate the moles of H_2O using dimensional analysis. (Learning Objective 1.1.A and Skill 5.F from the *AP Chemistry Course and Exam Description*)
- Part A (ii) requires students to determine the moles of hydrogen in the H_2O from part A (i) and then determine the empirical formula of ascorbic acid from combustion analysis data. The first point's (Point 02) intent was for students to use the answer from part A (i), the formula of H_2O , and dimensional analysis to determine the moles of hydrogen. The moles of hydrogen, when compared to the provided moles of CO_2 and the provided C:O mole ratio, should then lead to the empirical formula of ascorbic acid to earn the second point (Point 03). (4.5.A; 5.F and 1.3.A; 3.B)
- Part B (i) requires students to determine the molar concentration of the ascorbic acid solution from the titration information. The intent was for students to identify the equivalence point of the titration from the provided titration curve and use the data to calculate the molarity of the ascorbic acid solution. Correct responses used dimensional analysis. (8.5.A; 5.F)
- Part B (ii) requires students to analyze a titration curve to determine the $\text{p}K_a$ for ascorbic acid. The intent was for students to have experience interpreting acid-base titration curves and to know that the $\text{p}K_a$ equals the pH of the solution at the half-equivalence point on a titration curve. (8.5.A; 2.D)
- Part B (iii) requires students to calculate the value of the ratio of $[\text{Asc}^-] / [\text{HAsc}]$ at a given pH. The intent was for students to use the $\text{p}K_a$ from Part B (ii) and the given pH in the Henderson-Hasselbalch equation, or a K_a expression, to solve for the ratio. (8.9.A; 5.F)
- Part C (i) requires students to explain how the data provided supports that HAsc undergoes first order kinetics when reacting with the triiodide ion. The intent was for students to support a claim of first order kinetics with respect to HAsc with either a calculation or a description using the data from trials 1 and 3. (5.2.A; 6.B)

- Part C (ii) requires students to calculate the value of the rate constant for the reaction (Point 08) and include units (Point 09) using the provided data from any trial and the integrated rate law. The intent was for students to use provided data from any trial and the integrated rate law to calculate the value of k and to provide the correct units. (5.2.A; 5.F)
- Part D requires students to identify an intermolecular force that exists between I_3^- and H_2O that does not occur between I_2 and H_2O . The intent was for students to state or describe that ion-dipole forces are present between the I_3^- and H_2O , while ion-dipole forces of attraction are not present between I_2 and H_2O . (3.1.A; 4.C)

How well did the responses address the course content related to this question? How well did the responses integrate the skill(s) required on this question?

The mean score for Question 2 was 4.29 out of a possible 10 points. The total score distribution and the point-by-point distribution on this question are shown in the following figures.



- Part A (i) was the most accessible to students. Successful responses showed dimensional analysis to arrive at the correct number of moles of H_2O .
- Part A (ii) These two points were difficult for students to obtain. Successful responses related the moles of H_2O to the moles of hydrogen present (Point 02) from the answer obtained in A (i) and then used the mole-to-mole ratio of C:H:O to arrive at the correct empirical formula (Point 03).
- Part B (i) was also challenging for students. Successful responses used the provided molarity with the volume of NaOH identified at the equivalence point on the graph to calculate moles of NaOH and then either showed or made implicit the 1:1 mole ratio of NaOH:HAsc to finally calculate the correct molarity of HAsc, using the provided volume of HAsc.
- Part B (ii) was moderately accessible for students. Successful responses expressed the knowledge that $\text{p}K_a$ equals pH at the half-equivalence point to determine the correct $\text{p}K_a$.
- Part B (iii) was much less accessible for students than B (ii). Successful responses utilized the Henderson-Hasselbalch equation to arrive at the correct $[\text{Asc}^-] / [\text{HAsc}]$ or used a K_a expression to solve for the correct ratio.
- Part C (i) was somewhat accessible to students. Successful responses stated that between trials 1 and 3, the $[\text{I}_3^-]$ was held constant while both the $[\text{HAsc}]$ and rate of reaction doubled, making the reaction first order with respect to HAsc. Other successful responses took the ratio of the data from trials 1 and 3 to solve for the order of HAsc.
- Part C (ii) The first point (Point 08) was very accessible for students. Successful responses used data from any of the three trials and the integrated rate law to solve for the rate law constant, k . The second point (Point 09) was much less accessible. Successful responses reported the correct units of $\text{M}^{-1} \text{s}^{-1}$.
- Part D was the least accessible for students. Successful responses stated or described that ion-dipole forces were present between I_3^- and H_2O .

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> |
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| Part A (i) – Point 01 <ul style="list-style-type: none"> • A typical error was incorrect rounding. • Another error was using the incorrect molar mass of H_2O. | Part A (i) – Point 01 <ul style="list-style-type: none"> • $2.883 \text{ g H}_2\text{O} \times \frac{1 \text{ mol H}_2\text{O}}{18.02 \text{ g H}_2\text{O}} = 0.1600 \text{ mol H}_2\text{O}$ |
| Part A (ii) – Point 02 <ul style="list-style-type: none"> • A typical error was due to an incorrect calculation of moles of hydrogen, usually using the 0.1600 mol from the answer in part A (i) rather than multiplying by 2. | Part A (ii) – Point 02 <ul style="list-style-type: none"> • $0.1600 \text{ mol H}_2\text{O} \times \frac{2 \text{ mol H}}{1 \text{ mol H}_2\text{O}} = 0.3200 \text{ mol H}$ |

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| <p>Part A (ii) – Point 03</p> <ul style="list-style-type: none"> A common error on point 3 was using 0.1600 mol of CO₂ rather than the 0.2400 mol of CO₂ provided. | <p>Part A (ii) – Point 03</p> <ul style="list-style-type: none"> $x : y : z = (\text{moles of C}) : (\text{moles of H}) : (\text{moles of O})$ $x : y : z = 0.2400 : 0.3200 : 0.2400 = 3 : 4 : 3$ Therefore, the empirical formula of ascorbic acid is C₃H₄O₃. $0.2400 \text{ mol CO}_2 \times \frac{1 \text{ mol C}}{1 \text{ mol CO}_2} = 0.2400 \text{ mol C}$ $\frac{0.3200 \text{ mol H}}{0.2400 \text{ mol C}} = \frac{4 \text{ H}}{3 \text{ C}}$ Given that the ratio of C:O is 1:1, the empirical formula of ascorbic acid is C₃H₄O₃. |
| <p>Part B (i) – Point 04</p> <ul style="list-style-type: none"> The $M_1V_1 = M_2V_2$ formula was often employed rather than showing the mole-to-mole conversion. This work with a correct answer earned the point only because of the 1 mol NaOH:1 mol HAsc ratio for this system. A common error was using the volume of HAsc to find the moles of NaOH and then using the volume of NaOH to find the molarity of HAsc. Other common errors were using the total volume of NaOH from the graph (20 mL) or adding the volume of the HAsc to the volume of NaOH (26 mL). | <p>Part B (i) – Point 04</p> <ul style="list-style-type: none"> $0.0160 \text{ L NaOH} \times \frac{0.0550 \text{ mol NaOH}}{1 \text{ L NaOH}} \times \frac{1 \text{ mol HAsc}}{1 \text{ mol NaOH}}$ $= 8.80 \times 10^{-4} \text{ mol HAsc}$ $\frac{8.80 \times 10^{-4} \text{ mol HAsc}}{0.0100 \text{ L}} = 0.0880 \text{ M HAsc}$ |
| <p>Part B (ii) – Point 05</p> <ul style="list-style-type: none"> A common error was not realizing that pH = pK_a at the half-equivalence point, or at 8 mL in this titration curve. Some responses reported the pK_a as 7.5, the pH at the equivalence point. | <p>Part B (ii) – Point 05</p> <ul style="list-style-type: none"> Correctly approximating the pK_a to be 4.1, or in the range of 4.0–4.3, from half-equivalence point on the titration curve. |
| <p>Part B (iii) – Point 06</p> <ul style="list-style-type: none"> Common errors included using ln or e^x, rather than 10^x, to solve for $\frac{[\text{Asc}^-]}{[\text{HAsc}]}$. Another typical error was using 10^{-(pH-pK_a)}, illustrating that students are accustomed to using 10^{-pH} to solve for [H⁺]. Several responses set up the calculation correctly but did not solve for the ratio. | <p>Part B (iii) – Point 06</p> <ul style="list-style-type: none"> $\text{pH} = \text{pK}_a + \log \left(\frac{[\text{Asc}^-]}{[\text{HAsc}]} \right)$ $4.7 = 4.1 + \log \left(\frac{[\text{Asc}^-]}{[\text{HAsc}]} \right)$ $\frac{[\text{Asc}^-]}{[\text{HAsc}]} = 10^{0.6} = 4.0$ |

| | |
|---|--|
| <p>Part C (i) – Point 07</p> <ul style="list-style-type: none"> A typical error was omitting either reference to trials 1 and 3 or to the fact that $[I_3^-]$ is constant, or omitting both references, all of which did not earn the point. Another common error was giving a vague description of when concentration doubled so did the rate, without stating which specific substance's concentration doubled, without stating that $[I_3^-]$ was constant, or without referencing trials 1 and 3. | <p>Part C (i) – Point 07</p> <ul style="list-style-type: none"> $\frac{4.914 \times 10^{-4}}{2.457 \times 10^{-4}} = \left(\frac{0.900}{0.450}\right)^a$ thus $a = 1$. Comparing trials 1 and 3, the rate doubles when the $[HAsc]$ is doubled, and the $[I_3^-]$ is constant, indicating that the process is first order with respect to $HAsc$. |
| <p>Part C (ii) – Point 08</p> <ul style="list-style-type: none"> A common error was omitting the $\times 10^{-4}$ from the scientific notation in the answer. | <p>Part C (ii) – Point 08</p> <ul style="list-style-type: none"> Using trial 1 data: $k = \frac{rate}{[HAsc][I_3^-]} = \frac{2.457 \times 10^{-4} M/s}{(0.450 M)(1.200 M)}$ $= 4.55 \times 10^{-4} M^{-1} s^{-1}$ |
| <p>Part C (ii) – Point 09</p> <ul style="list-style-type: none"> Typical errors included reporting the incorrect units, such as M/s, or omitting units altogether. | <p>Part C (ii) – Point 09</p> <ul style="list-style-type: none"> $M^{-1} s^{-1}$ |
| <p>Part D – Point 10</p> <p>The most common errors were stating one of the following:</p> <ul style="list-style-type: none"> Dipole-dipole forces are present between I_3^- and H_2O. That I_3^- bonded to H_2O. Describing an incorrect intermolecular force. Ion-induced-dipole is present between I_3^- and H_2O. | <p>Part D – Point 10</p> <ul style="list-style-type: none"> Ion-dipole attractions are present between I_3^- ions and water, but not between I_2 molecules and water. |

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

- **Mole Ratios:** Be sure students have experience calculating moles and applying those moles as ratios to determine an empirical formula.
- **Perform Experiments:** Students perform better on experiment-based questions when they have experienced a similar lab experiment in class. Have students perform acid-base titrations and reaction rates experiments in class.
- **Graphical Interpretation:** Be sure students have experience interpreting titration curves. Students should be able to describe the characteristics of a weak acid-strong base (and weak base-strong acid) titration at various points of the process, and they should recognize features of particulate diagrams that represent the following points:
 - Before the half-equivalence point
 - At the half-equivalence point
 - After the half-equivalence point
 - At the equivalence point
 - After the equivalence point
- **Calculations with log Terms:** Be sure students have experience with the Henderson-Hasselbalch equation and working with \log_{10} and inverse \log_{10} .
- **Kinetics:** Have students practice interpreting initial reaction rates data and concentration versus time data to determine orders of reactants. Additionally, have them practice calculating rate constants, including correct units.
- **Mixtures and Intermolecular Forces:** Be sure students are well-versed in the types of intermolecular forces and familiar with the interactions that occur in mixtures (not just pure substances).

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 and assign topic questions for Topics 1.1, 1.3, 3.1, 4.5, 5.2, 8.5, and 8.9.
- Teachers can use AP Classroom to direct students to the AP Exam On-Demand Review, 2024 Session 5: FRQ (Short)
- Teachers can have students perform laboratory investigations such as [Kinetics of Bleach and Food Coloring](#) or Investigations 10 and 11 from [AP Chemistry Guided Inquiry Experiments](#). As a formative or summative assessment after completing the lab, teachers can use [2015 Free-Response Question 5](#).
- Teachers can utilize the [Particulate Diagrams for Acid-Base Titrations](#) activity by Michael Farabaugh, available in the [Online Teacher Community Resources](#) section.
- Teachers can also create custom quizzes from previously administered AP Exam items from the Question Bank and filter for Skills 2.C, 2.D, and 6.B, which relate to experimentation skills and supporting claims with experimental evidence.

Question 3

Task: Phosphorus

Topic: Lewis Diagrams, Entropy, Thermodynamic Favorability, Heat Capacity and Calorimetry, Enthalpy of Reaction, Hess's Law, Equilibrium Constant, Le Châtelier's Principle

| | Max Points: | Mean Score: |
|--------------------------|-------------|-------------|
| Point 01 | 1.0 | 0.73 |
| Point 02 | 1.0 | 0.25 |
| Point 03 | 1.0 | 0.35 |
| Point 04 | 1.0 | 0.06 |
| Point 05 | 1.0 | 0.28 |
| Point 06 | 1.0 | 0.38 |
| Point 07 | 1.0 | 0.31 |
| Point 08 | 1.0 | 0.52 |
| Point 09 | 1.0 | 0.43 |
| Point 10 | 1.0 | 0.31 |
| Overall Mean Score: 3.61 | | |

What were the responses to this question expected to demonstrate?

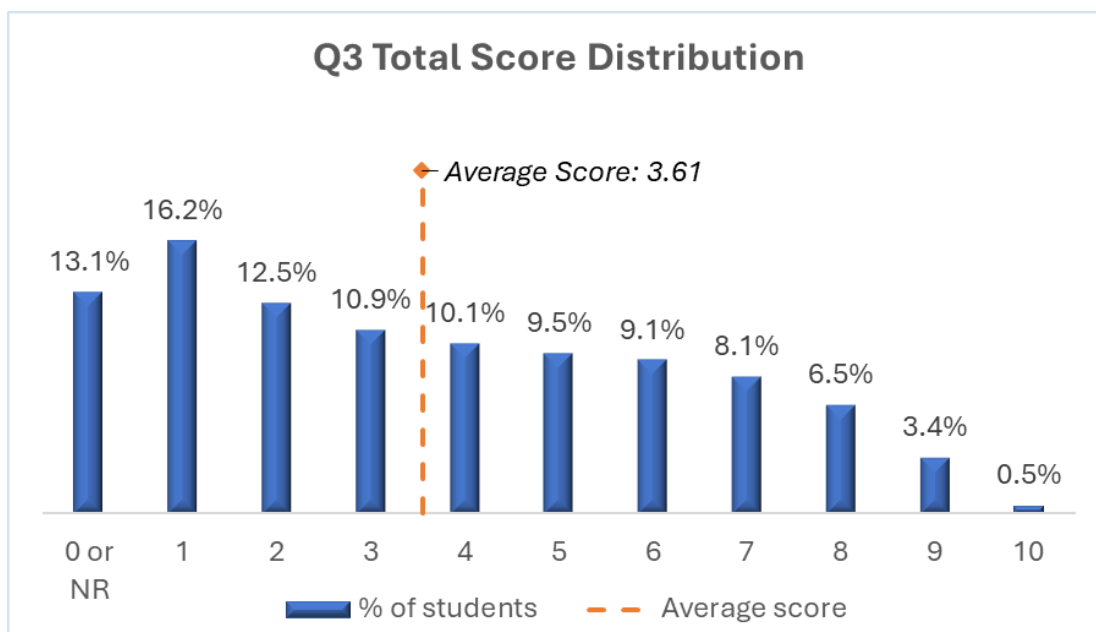
Question 3 presents students with a series of questions related to reactions involving various phosphorus compounds. This question focuses on understanding various topics related to thermodynamics and equilibrium.

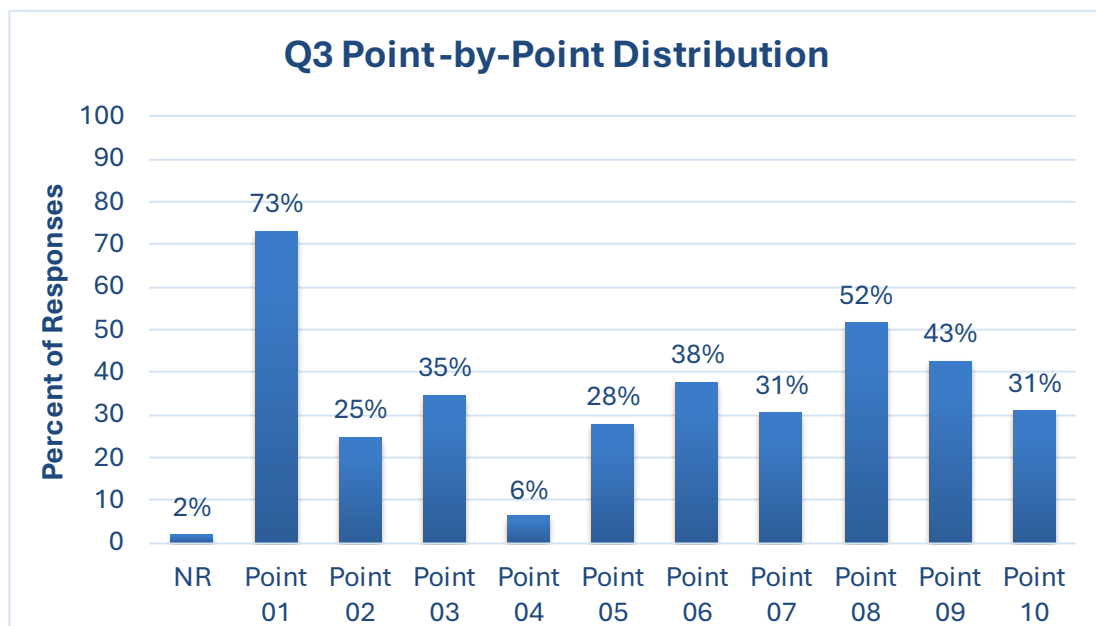
- Part A requires students to complete a Lewis diagram for P_4 by adding two nonbonding electrons to each phosphorus atom in the provided diagram. The intent was for students to complete the octet for each atom in the diagram. (Learning Objective 2.5.A and Skill 3.B from the *AP Chemistry Course and Exam Description*)
- Part B (i) requires students to explain why the entropy of a reaction decreases using particle-level reasoning and a discussion that involves the given reaction. The intent was for students to describe that matter is more dispersed as a gas (in the reactants) compared to less dispersed as a solid (in the products). (9.1.A; 4.A)
- Part B (ii) requires students to predict and discuss what drives the thermodynamic favorability of a reaction based on the change in enthalpy and change in entropy using the mathematical relationship $\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$ to justify their answer. The intent was for students to discuss how a $\Delta H^\circ < 0$ contributes to favorability of the reaction while a $\Delta S^\circ < 0$ does not contribute to favorability. (9.3.A; 6.D)
- Part C (i) requires students to calculate the heat released in a calorimetry experiment based on the data provided. The response should be reported with the correct number of significant figures. The intent was for students to quantitatively connect the experimental data provided to the magnitude of the heat change. (6.4.A; 5.F)
- Part C (ii) requires students to use the calculated heat released (answer from Part C (i)) and the provided mass of the reactant, to calculate the $\Delta H_{\text{rxn}}^\circ$. The final answer must also include a negative sign to indicate that the reaction is exothermic. The intent was for students to combine the value of heat calculated in C (i) with the stoichiometry of the reaction to calculate the $\Delta H_{\text{rxn}}^\circ$. (6.6.A; 5.F)
- Part D requires students to analyze an experimental error where less limiting reactant (solid) is transferred to the calorimeter. The intent is for students to predict that the error will result in a measured change in temperature that is less than the first trial and correctly justify their answer using a logical description of how the thermal energy released in a reaction depends on the amount of limiting reactant. (6.4.A; 6.G)

- Part E requires students to use Hess's law and the pair of provided reaction enthalpies to solve for the ΔH_f° of PCl_5 . The intent was for students to analyze the series of reactions provided and determine how those two steps combine to result in the overall desired reaction and use that information to calculate the ΔH_f° of PCl_5 . (6.9.B; 5.F)
- Part F (i) requires students to set up and solve an expression for K_p using a particle-level diagram representing the species present at equilibrium. The intent was for students to identify and count the various reactants and products present in the equilibrium as shown in the particle-level diagram and use that quantitative data to calculate the K_p value. (7.4.A; 5.F)
- Part F (ii) requires students to use the sign of the provided ΔH_f° to predict that the K_p will decrease when the temperature of the reaction is increased. The intent was for students to recognize that an exothermic reaction will favor the reactants at high temperatures and therefore an increase in temperature will shift the reaction toward increased reactants and lower K_p . (7.10.A; 6.D)

How well did the responses address the course content related to this question? How well did the responses integrate the skill(s) required on this question?

The mean score for Question 3 was 3.61 out of a possible 10 points. The total score distribution and the point-by-point distribution on this question are shown in the following figures.

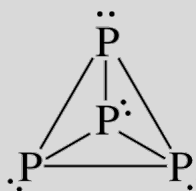




- Part A was the most accessible point for students, where they successfully added two electrons to each P on the diagram and completed the respective valence shell with a total of eight electrons. The most common error was omitting the electrons on the central P atom.
- Part B (i) was very challenging for students. Some students correctly demonstrated an understanding of how entropy decreases in the reaction and were able to justify their answer with a particle-level discussion of the dispersal of gas particles versus solid particles or by discussing their respective number of microstates.
- Part B (ii) was slightly more accessible for students. Some students understood the mathematical relationship $\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$ and correctly discussed the signs of each term and how they contributed favorably or unfavorably to the overall thermodynamics. Many students attempted to answer the question but did not understand the correct mathematical relationship.
- Part C (i) was the least accessible point for students. Most students correctly used $q = mc\Delta T$ to calculate the heat released; however, they failed to report their answer to the correct number of significant figures. When students missed this point, it was more commonly missed due to the significant figures error than due to a misconception of the heat calculation.
- Part C (ii) was challenging for students. Many students used the grams of solid provided to correctly calculate the number of moles and use their answer in C (i) to calculate the ΔH_{rxn}° (Point 05). The second point (Point 06) in C (ii) was more accessible for students. Most students correctly included a negative sign to indicate that the overall reaction was exothermic.
- Part D was somewhat less accessible for students. Many students failed to explain the concept that a smaller quantity of limiting reactant added to the calorimeter produced less thermal energy and therefore resulted in a smaller change in temperature.
- Part E was the second most accessible part for students. Most students correctly used Hess's law and the data provided to calculate the ΔH_f° .
- Part F (i) was moderately accessible for students. Most students correctly set up an expression for K_p based on the given reaction, interpreted the particle-level diagram provided to determine the partial pressures for each species, and then calculated the correct K_p value. If students provided a correct expression and then didn't earn this point, it was commonly due to miscounting the number of the species in the diagram.

- Part F (ii) was less accessible for students. Only some students correctly discussed the relationship between an increase in temperature and a decrease in the K_p value due to a shift in the overall equilibrium. Many students struggled to connect the concept that exothermic reactions favor reactant formation at higher temperatures to a smaller K_p value.

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 – Point 01</p> <ul style="list-style-type: none"> Did not include lone pair electrons on the central P atom Included too many (four or six) additional electrons on each of the P atoms | <p>Part A – Point 01</p> <ul style="list-style-type: none"> Adding two lone pair electrons to each P in the diagram  |
| <p>Part B (i) – Point 02</p> <ul style="list-style-type: none"> Using a “less disorder/more order” justification without including a particle-level discussion of the reaction species No discussion of the states of matter and only discussing fewer moles of products compared to the moles of reactants Vague language that implies O_2 is experiencing a phase change from gas to solid | <p>Part B (i) – Point 02</p> <ul style="list-style-type: none"> Because gas particles are more dispersed (have more microstates) than solids, the entropy decreases as the reactants (which include a gas) convert to the solid product. A correct explanation of the differences between the gaseous reactants and the solid product with regards to one of the following: the number of possible microstates, degrees of freedom, particle orientations, dispersion of particles, or number of possible arrangements of particles. |
| <p>Part B (ii) – Point 03</p> <ul style="list-style-type: none"> Incorrect understanding of the criteria for thermodynamic favorability. Incorrect understanding of the mathematical relationship $\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$. Incorrectly stating that BOTH ΔH° and ΔS° contribute to the thermodynamic favorability. Some students transcribed all of the various mathematical relationships from the equation sheet but did not attempt to answer the actual prompt. | <p>Part B (ii) – Point 03</p> <ul style="list-style-type: none"> Agreement with the claim and correct discussion of the signs of ΔH° and ΔS° and how they contribute, or not, to the overall negative sign of ΔG°, which indicates a thermodynamically favorable reaction. Yes. Given that $\Delta G_{rxn}^\circ = \Delta H_{rxn}^\circ - T\Delta S_{rxn}^\circ$, the reaction must have $\Delta G_{rxn}^\circ < 0$ to be favorable. Because the reaction is exothermic, $\Delta H_{rxn}^\circ < 0$ and enthalpy contributes to favorability. $\Delta S_{rxn}^\circ < 0$, so entropy does not contribute to favorability. |

| | |
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| <p>Part C (i) – Point 04</p> <ul style="list-style-type: none"> Incorrect use of only the mass of the solid (0.1 g) and not the total mass of the solution (100.1 g) Reporting the final answer to the incorrect number of significant figures | <p>Part C (i) – Point 04</p> <ul style="list-style-type: none"> A correctly calculated value of heat reported to the correct number of significant figures $q = mc\Delta T$ $q = (100.1 \text{ g})(4.18 \text{ J/(g} \cdot ^\circ\text{C)})(22.38^\circ\text{C} - 22.00^\circ\text{C})$ $q = 160 \text{ J} = 0.16 \text{ kJ}$ |
| <p>Part C (ii) – Point 05</p> <ul style="list-style-type: none"> Misunderstanding how to calculate the ΔH_{rxn}° from the q value calculated in Part C (i) Trying to use a ΔH_{rxn}° formula based on ΔH_f° values for reactants and products (but this information was not provided) | <p>Part C (ii) – Point 05</p> <ul style="list-style-type: none"> $q_{rxn} = -q_{surr} = -0.16 \text{ kJ}$ $\Delta H_{rxn}^\circ = \frac{-0.16 \text{ kJ}}{0.100 \text{ g P}_4\text{O}_{10}} \times \frac{283.9 \text{ g P}_4\text{O}_{10}}{1 \text{ mol P}_4\text{O}_{10}} \times \frac{1 \text{ mol P}_4\text{O}_{10}}{1 \text{ mol}_{rxn}}$ $\Delta H_{rxn}^\circ = -450 \text{ kJ/mol}_{rxn}$ |
| <p>Part C (ii) – Point 06</p> <ul style="list-style-type: none"> Not relating the increase in temperature from the data table to the fact that the reaction is exothermic, and therefore not including a negative sign with ΔH_{rxn}° | <p>Part C (ii) – Point 06</p> <ul style="list-style-type: none"> Including the correct negative sign on the final answer for ΔH_{rxn}° |
| <p>Part D – Point 07</p> <ul style="list-style-type: none"> Explanations implying a warm solid was placed into water, causing the ΔT; therefore, less of the solid transferred correlates to less heat transferred to the solution No explanation that less limiting reactant (fewer moles of chemical reaction) produces a smaller thermal energy transfer | <p>Part D – Point 07</p> <ul style="list-style-type: none"> A correct prediction that if less limiting reactant is transferred, then less heat will be produced from the chemical reaction and will therefore result in a smaller ΔT. Less than. If less P_4O_{10} is present, less thermal energy will be transferred to the water during the reaction, causing the temperature increase to be less than it was with 0.100 g of P_4O_{10}. |
| <p>Part E – Point 08</p> <ul style="list-style-type: none"> Incorrectly adding $\Delta H_1^\circ + \Delta H_2^\circ$ without recognizing the chemical equations combined must add to the overall equation | <p>Part E – Point 08</p> <ul style="list-style-type: none"> A correct Hess's law analysis to combine the ΔH_1° and ΔH_2° terms from the two provided reactions: $\Delta H_{f, \text{PCl}_5(\text{g})}^\circ = \frac{1}{4} \Delta H_1^\circ + \Delta H_2^\circ$ $\Delta H_{f, \text{PCl}_5(\text{g})}^\circ = \frac{1}{4}(-1148) + (-88) = -375 \text{ kJ/mol}$ |

| | |
|---|--|
| <p>Part F (i) – Point 09</p> <ul style="list-style-type: none"> The most common error was a misunderstanding of how to set up a K_p expression. Not understanding how to use the particle diagram to determine the partial pressures of the reaction species. The most common incorrect result was $K_p = 1 \text{ atm}$. | <p>Part F (i) – Point 09</p> <ul style="list-style-type: none"> Correctly setting up the K_p expression from the balanced reaction, using the particle-level diagram to determine the partial pressures of the reaction species, and then calculating the K_p using the expression and the determined values $K_p = \frac{P_{\text{PCl}_3}}{(P_{\text{PCl}_3})(P_{\text{Cl}_2})} = \frac{4.00}{(2.00)(6.00)} = \frac{1}{3} = 0.333$ |
| <p>Part F (ii) – Point 10</p> <ul style="list-style-type: none"> A misunderstanding of how raising the temperature affects the K_p of an exothermic reaction Incorrectly discussing how an increased temperature will increase the pressure of the system (using gas laws rather than using reasoning based on the equilibrium position) | <p>Part F (ii) – Point 10</p> <ul style="list-style-type: none"> A correct discussion of how increasing the temperature of an exothermic reaction shifts the equilibrium (favors reactants) and decreases the K_p |

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

- Significant Figures:** Students should be familiar not only with the rules for multiplication and division but also with the rules for addition/subtraction. Have them practice working with numbers from real experimental data and calculating “changes” in volume or temperature to practice working with data of various levels of precision.
- Entropy:** When teaching the concept of entropy, have students practice discussing how, when, and why entropy changes in various physical and chemical changes. Students struggled describing the chemical conversion of solid + gas (reactants) to a solid compound (product); their language was often generic and did not explicitly discuss the concept of dispersion or microstates. If a prompt asks students to explain a phenomenon on the particle level, be sure that students use the behavior of particles in their explanations.
- Thermodynamic Favorability:** Ensure students are familiar with the definition of thermodynamic favorability and the mathematical relationship $\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$. Students should practice predicting and describing the conditions under which various reactions are thermodynamically favorable and discussing how the magnitude and signs of ΔH° and ΔS° contribute to the overall sign of ΔG° and what that means in relation to the favorability.
- General Logical Connections:** Students should have practice justifying their qualitative answers with logical connections between concepts. Give them practice writing statements based on error analysis or changes in conditions and how those would impact the system or reaction provided. Have students analyze released [sample responses from AP Central](#) in small groups, and have them make suggestions for (or rewrite) the responses to improve the clarity and chemical accuracy of the responses.

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 and assign topic questions for Topics 2.5, 6.4, 6.6, 6.9, 7.4, 7.10, 9.1, and 9.3.
- Teachers can use AP Classroom to direct students to the AP Exam On-Demand Reviews:
 - 2024 Session 6: FRQ (Long) – $\text{CaCO}_3 + \text{HCl}$
 - 2024 Session 8: FRQ (Long)
- To improve students understanding of entropy on the conceptual and particle level, teachers can utilize:
 - The PhET simulation on [Entropy, Microstates, and Probability](#)
 - The TED-Ed video “[What is Entropy?](#)”
- To understand why “order” and “disorder” are poor descriptors of the entropy of solids, liquids, and gases, teachers can refer to the LibreTexts article, “[‘Disorder’ in Thermodynamic Entropy](#)” for a thorough analysis.

Question 4

Task: Methanol and Formaldehyde

Topic: Hybridization; Intermolecular Forces; Solids, Liquids and Gases; Energy of Phase Changes

| | Max Points: | Mean Score: |
|--------------------------|-------------|-------------|
| Point 01 | 1.0 | 0.56 |
| Point 02 | 1.0 | 0.48 |
| Point 03 | 1.0 | 0.74 |
| Point 04 | 1.0 | 0.54 |
| Overall Mean Score: 2.32 | | |

What were the responses to this question expected to demonstrate?

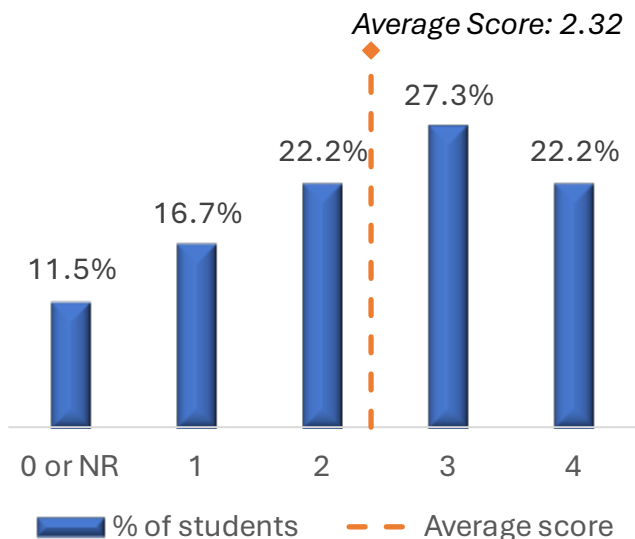
Question 4 presents students with an array of questions related to a mixture of methanol and formaldehyde.

- Part A requires students to identify the hybridization of C in H_2CO . The intent was for students to use the provided Lewis diagram to determine the arrangement of electrons around the C atom and thus the hybridization. (Learning Objective 2.7.A and Skill 1.A from the *AP Chemistry Course and Exam Description*)
- Part B requires students to draw a dashed line that represents a hydrogen bonding attraction between one methanol molecule and one formaldehyde molecule in a particle level diagram of the mixture. The intent was for students to identify the appropriate atoms in each type of molecule for this interaction and draw the dashed line to represent the hydrogen bonding attraction. (3.1.A; 3.C)
- Part C (i) requires students to propose a temperature at which both gases in the mixture would condense into liquids. The intent was for students to utilize melting and boiling point data from a table to determine an appropriate temperature. (3.3.A; 2.C)
- Part C (ii) requires students to calculate the thermal energy that must be removed to condense a given mass of CH_3OH . The intent was for students to convert the mass of methanol to moles and then multiply that value by the correct enthalpy of vaporization from the table to determine the thermal energy removed during condensation. (6.5.A; 5.F)

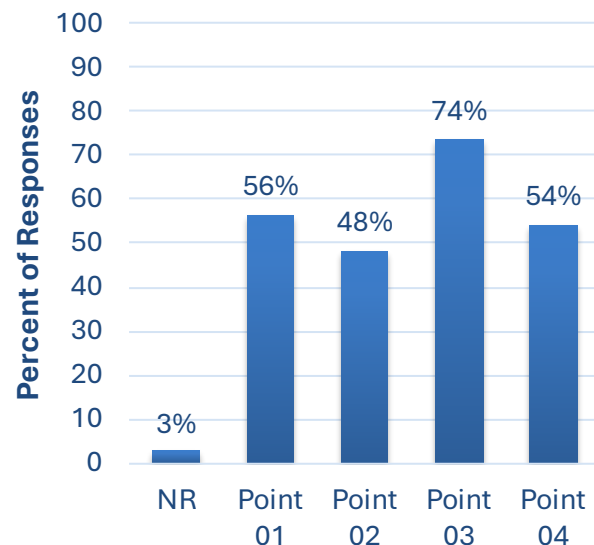
How well did the responses address the course content related to this question? How well did the responses integrate the skill(s) required on this question?

The mean score on Question 4 was 2.32 out of a possible 4 points. The total score distribution and the point-by-point distribution on this question are shown in the following figures.

Q4 Total Score Distribution

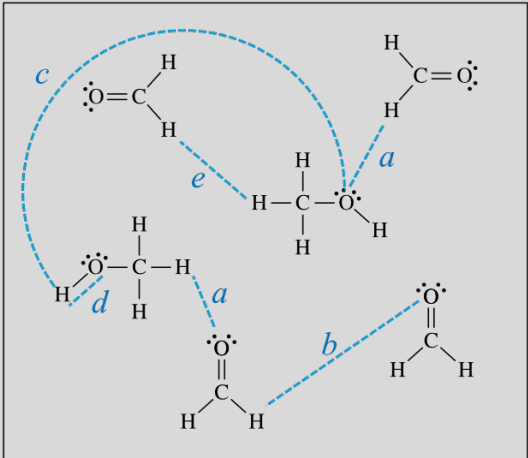
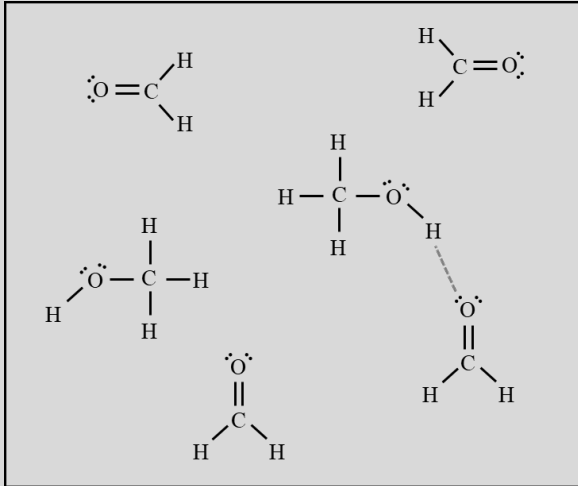


Q4 Point-by-Point Distribution



- Part A was a moderately accessible point. Correct responses correctly identified the hybridization of the valence orbitals of the C atom in H_2CO as sp^2 .
- Part B was a slightly less accessible point. Correct responses correctly drew a hydrogen bonding attraction between the two molecules stated in the prompt by identifying a H atom of the hydroxyl ($-\text{OH}$) group on a CH_3OH molecule Lewis structure and drawing a dashed line connecting it to the oxygen atom in a H_2CO molecule Lewis structure.
- Part C (i) was the most accessible point with responses stating a temperature value that fell in the range of 181 K to 254 K. Converting temperatures from kelvins to degrees Celsius and then stating a temperature in the degrees Celsius range (-92°C to -19°C) was a less common correct response.
- Part C (ii) was a moderately accessible computation point with many responses explicitly or implicitly converting the given mass of CH_3OH to moles and then explicitly converting that value to kilojoules by selecting the correct enthalpy of vaporization from the data table, 37.6 kJ/mol.

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 – Point 01</p> <ul style="list-style-type: none"> Identifying four shared pairs of electrons on the C of H_2CO, rather than the three bonding regions, as the information needed to determine hybridization led to incorrect hybridization (sp^3). Instead of stating hybridization, many incorrect responses provided one the following: sigma and pi bond counts, electron configuration notations, orbital filling diagrams, or molecular geometries. | <p>Part A – Point 01</p> <ul style="list-style-type: none"> sp^2 hybridization. |
| <p>Part B – Point 02</p> <ul style="list-style-type: none"> The most common incorrect response was drawing an interaction that was not a hydrogen bonding attraction, such as drawing an attraction between the O of CH_3OH to a H of H_2CO (see dashed lines <i>a</i> in the following diagram). Though O is a highly electronegative atom, the H atoms of H_2CO are bonded to a C atom and will not have a large enough dipole to participate in hydrogen bonding attractions. It is the high polarity of the H <u>intramolecularly</u> bonded to the O in CH_3OH that is critical for the <u>intermolecular</u> force. The polarity of the O–H bond, the sizeable partial negative charge on O in H_2CO, and the small size of the H atom's electron cloud are three factors leading to the strong hydrogen bonding interaction.  | <p>Part B – Point 02</p> <ul style="list-style-type: none"> Correct responses drew a dashed line to represent one of the eight possible hydrogen bonding attractions in the diagram given the constraints in the prompt.  <p>The best responses chose an appropriate H atom that was in close proximity to an appropriate O atom.</p> |

| | |
|--|---|
| <ul style="list-style-type: none"> • Instead of drawing an attraction between a molecule of CH_3OH and a molecule of H_2CO as specifically stated in the prompt, responses drew dashed lines between molecules of the same type: two H_2CO molecules (dashed line <i>b</i>) or two CH_3OH molecules (dashed line <i>c</i>). • Some responses changed the prompt by adding water molecules to the diagram to provide a familiar opportunity to identify hydrogen bonding attractions, rather than identifying the intermolecular attractions between the molecules provided and asked for in the prompt. • Additional incorrect responses included circling or drawing dashed lines between H and O within one molecule (dashed line <i>d</i>), indicating a misunderstanding of the difference between <u>inter</u>molecular forces and <u>intra</u>molecular bonds. • Some responses drew a line between two H atoms (dashed line <i>e</i>), instead of between an H atom in CH_3OH and an O atom in H_2CO. | |
| <p>Part C (i) – Point 03</p> <ul style="list-style-type: none"> • Providing a single-sided range: “greater than 181 K,” “cooled to less than 254 K,” or “253 K so both of them will be liquids; anything less than 254 K” • Providing a range with one or more boundaries that expands beyond the acceptable range: “around 181 K” includes temperatures below 181 K as well • Incorrectly converting to Celsius: 200°C | <p>Part C (i) – Point 03</p> <ul style="list-style-type: none"> • Providing a temperature in range of 181 K – 254 K |
| <p>Part C (ii) – Point 04</p> <ul style="list-style-type: none"> • Correct response with no supporting work. • Using enthalpy of vaporization of H_2CO rather than the enthalpy of vaporization of CH_3OH. | <p>Part C (ii) – Point 04</p> <ul style="list-style-type: none"> • Correctly converting grams of CH_3OH to moles and multiplying by the correct enthalpy of vaporization to calculate the kJ of the thermal energy removed • $8.59 \text{ g CH}_3\text{OH} \times \frac{1 \text{ mol}}{32.04 \text{ g}} \times \frac{-37.6 \text{ kJ}}{1 \text{ mol CH}_3\text{OH}} = -10.1 \text{ kJ}$ |

- Making algebraic errors when solving for the amount of energy removed, most commonly incorrectly using the reciprocal of the enthalpy value. These errors would result in final units other than kJ, and the prompt asks for a calculation that yields kJ. Absence of units in the calculation setup prevented students from using this self-assessment tool.

$$\circ \quad 8.59 \times \frac{1}{32.04} \times \frac{1}{-37.6} = -0.00713$$

actual unit: $\frac{\text{mol}^2}{\text{kJ}}$

$$\circ \quad \frac{37.6}{8.59} \div 32.04 = 0.137$$

actual unit: $\frac{\text{kJ}}{\text{g}^2}$

$$\circ \quad \frac{37.6 \frac{\text{kJ}}{\text{mol}}}{0.268 \text{ mol CH}_3\text{OH}} = 140.$$

actual unit: $\frac{\text{kJ}}{\text{mol}^2}$

- Treating enthalpy of vaporization as a formula with which to substitute the number of moles in the denominator rather than kJ per 1 mole:

$$\frac{37.6 \frac{\text{kJ}}{\text{mol}}}{0.268 \text{ mol CH}_3\text{OH}} = 140.$$

- Using $q = mc\Delta T$ by making up values for one or more of the variables:

$$\circ \quad q = (8.59)(37.6)(338) = 109,000 \text{ kJ}$$

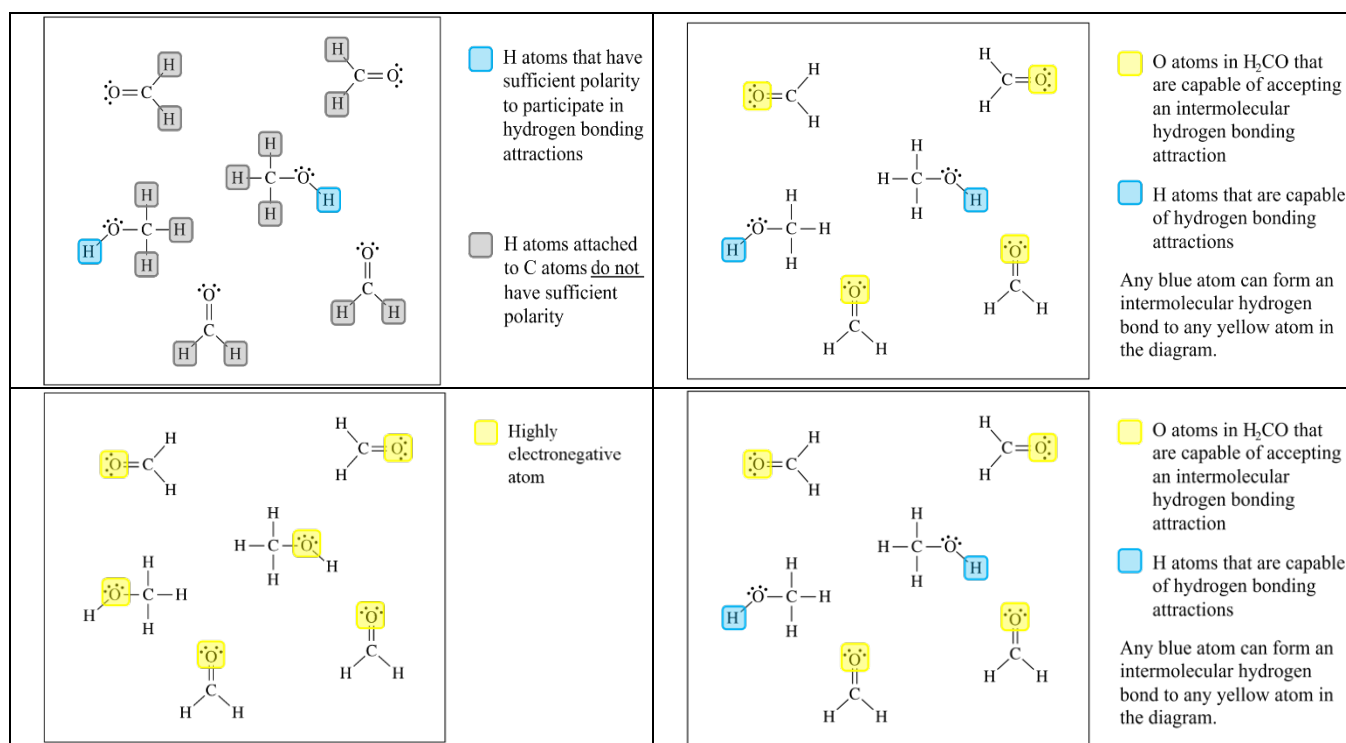
(an unreasonably large value for this context that results from using the enthalpy of vaporization as the specific heat capacity and the boiling point as the change in temperature)

$$\circ \quad q = \frac{8.59 \text{ g}}{32.04 \text{ g}} \times \frac{37.6 \text{ kJ}}{1 \text{ mol}} \times 1 \text{ K} = 10.1 \text{ kJ}$$

(calculates number of moles as m , uses the enthalpy of vaporization as c , and assumes a temperature change of 1 K)

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

- **Approaching Questions with Diagrams:** Students should look at all diagrams before reading the prompt. This will help them understand what is being asked.
- **Hybridization and VSEPR:** Be sure students understand the difference between hybridization and electron configuration. They should recognize that double and triple bonds only count as one electron domain.
- **Hydrogen Bonding:** Require students to identify what must be present to create a hydrogen bonding attraction, not just the conditions but the rationale as well. There must be a hydrogen permanently (intramolecularly) bonded to a highly electronegative atom (N, O, or F). The highly electronegative atom withdraws significant electron density from the H, giving the H a partial positive charge that it will strongly attract to a highly electronegative atom (N, O, or F) in a different molecule that is in close proximity. This two-part condition is what differentiates the hydrogen bond attraction from a simple dipole-dipole attraction.
- **Particle Diagram Assessment:** Have students manipulate particulate diagrams of mixtures with intermolecular forces. Many students associate H_2O or two molecules of the same substance when thinking about hydrogen bond attractions. Use examples of mixtures that are not aqueous and unfamiliar molecules in particulate diagrams.
 - **TIP:** Provide three copies of a diagram of a mixture in which water is not included. 2025 AP Chemistry Exam Question 4 part B is a great example.
 - On the first copy, ask students to color code all H atoms as blue if that hydrogen meets the criteria to have sufficient polarity and gray if the H atom does not have sufficient polarity.
 - On the second copy, highlight all N, O, or F atoms in yellow.
 - The blue-coded H atoms and yellow-coded O atoms from both diagrams are the only potential hydrogen bonding participants.
 - On a third copy, use the same color coding to highlight only atoms that address the prompt and can participate in hydrogen bonding attraction. In Question 4, we exclude oxygens of CH_3OH molecules because they are the only appropriate H source. In the 2025 Question 4 example, this would only leave eight possible hydrogen bond attractions.



- **Data Analysis:** Ensure that students have practice with selecting appropriate data with units from tables of information.
- **Show Work and Units:** Expect students to show work with all calculations and use units on the values in their intermediate steps. Have students check their work by analyzing the units in their setup.
 - **TIP:** Intentionally select unidentifiable response examples from former student work or [AP Chemistry Exam sample responses](#) where units were omitted. Have students score the work and determine what the final answer units would be given the incorrect setup.

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 and assign topic questions for Topics 2.7, 3.1, 3.3, and 6.5.
- Teachers can use AP Classroom to direct students to the AP Exam On-Demand Review 2023 Session 6: FRQ (Long) – Aluminum Redox.
- Teachers can have students analyze and critique [sample responses from AP Central](#) and rewrite them for clarity and chemical accuracy.

Question 5

Task: C₄H₉OH and Silanol

Topic: VSEPR, Intermolecular Forces, Properties of Solids, Ideal Gas Law

| | Max Points: | Mean Score: |
|--------------------------|-------------|-------------|
| Point 01 | 1.0 | 0.65 |
| Point 02 | 1.0 | 0.16 |
| Point 03 | 1.0 | 0.44 |
| Point 04 | 1.0 | 0.63 |
| Overall Mean Score: 1.88 | | |

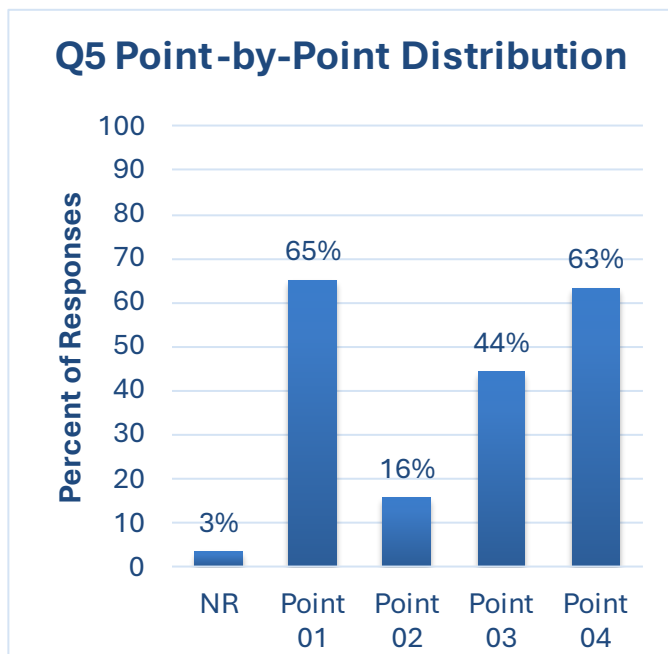
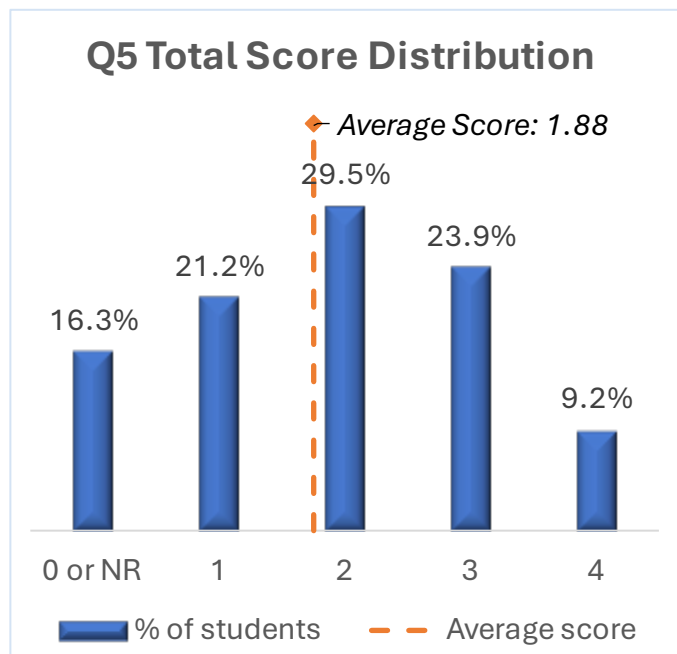
What were the responses to this question expected to demonstrate?

Question 5 presents students with a series of questions concerning *tert*-butyl alcohol (compound X) and trimethylsilanol (compound Y).

- Part A requires students to predict the geometry around the Si atom in compound Y. The intent was for students to demonstrate an understanding of the rules for predicting molecular geometry based on a Lewis structure. (Learning Objective 2.7.A and Skill 1.A from the *AP Chemistry Course and Exam Description*)
- Part B requires students to agree or disagree with a student claim that compound Y has a higher boiling point than compound X because compound Y has stronger London dispersion forces. The intent was for students to compare the number of occupied electron shells in the central C and Si atoms to explain the relative strengths of the intermolecular forces present in each substance. (3.1.A; 6.C)
- Part C requires students to justify which of the two compounds will have the higher vapor pressure when heated to 82°C. The intent was for students to demonstrate an understanding of the relationship between the strength of intermolecular forces and vapor pressure. (3.2.A; 6.E)
- Part D requires students to calculate the number of moles of gas particles in a sealed, rigid container using the given volume, temperature, and pressure, assuming ideal behavior. The intent was for students to calculate the unknown moles of gas using the ideal gas law. (3.4.A; 5.F)

How well did the responses address the course content related to this question? How well did the responses integrate the skill(s) required on this question?

The mean score for Question 5 was 1.88 out of a possible 4 points. The total score distribution and the point-by-point distribution on this question are shown in the following figures.



- Part A was a very accessible point for students. Correct responses successfully determined that the geometry around Si in compound Y is tetrahedral based on the provided Lewis diagram.
- Part B was the most challenging point for students. Although many students correctly agreed with the claim, many struggled to sufficiently justify their answer. Correct responses indicated that compound Y has a larger, more polarizable electron cloud resulting in stronger London dispersion forces.
- Part C was a moderately accessible point for students. Correct responses chose compound X as having the higher vapor pressure at 82°C. Explanations could include either that compound X has weaker intermolecular forces than compound Y, or that at 82°C compound X has reached its boiling point, but compound Y has not. Correct responses compared compounds X and Y rather than focusing on only one compound.
- Part D was a very accessible point for students. Correct responses used the ideal gas law, $PV = nRT$ to successfully calculate the total moles of gas.

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 – Point 01</p> <ul style="list-style-type: none"> Geometries other than tetrahedral (e.g., “trigonal planar” or “quadrilateral”) Adding an extra word that makes the geometry incorrect or ambiguous (e.g., “tetrahedral pyramidal”) or listing more than one geometry Giving bond angles such as 109.5° without indicating the molecular geometry sp^3 or other hybridizations | <p>Part A – Point 01</p> <ul style="list-style-type: none"> tetrahedral |
| <p>Part B – Point 02</p> <ul style="list-style-type: none"> Citing the higher molar mass of compound Y as the only justification for stronger dispersion forces Relating the strengths of IMFs to dipole-dipole forces or hydrogen bonding Discussing bond strength rather than intermolecular forces Indicating that boiling involves breaking bonds Disagreeing with the claim | <p>Part B – Point 02</p> <ul style="list-style-type: none"> I agree. Because Si has more occupied electron shells than C, compound Y has a larger, more polarizable electron cloud. I agree. Because Si has more electrons than C, compound Y’s electron cloud is more polarizable. I agree. Because Si has more electrons than C, there are more opportunities for induced dipoles in compound Y. |
| <p>Part C – Point 03</p> <ul style="list-style-type: none"> Restating the boiling points without comparing them or relating them to the relative vapor pressures: “The boiling point of compound X is 82°C whereas the boiling point of compound Y is 98°C.” Describing only compound X without a comparison to compound Y: “Compound X has reached its boiling point, so it is becoming vapor.” Describing states without a justification: “Compound X is a gas and compound Y is a liquid.” Comparing rates of vaporization rather than amounts of vapor at 82°C: “Compound X is becoming a vapor faster than compound Y.” Choosing compound Y. | <p>Part C – Point 03</p> <ul style="list-style-type: none"> Compound X. The IMFs in compound X are weaker than in compound Y, so compound X will have the higher vapor pressure. Compound X. Vapor pressure and boiling point are inversely related. Compound X has a lower boiling point than compound Y, so compound X will have a higher vapor pressure. Compound X. At 82°C, compound X has reached its boiling point, but compound Y has not, so compound X will have a higher vapor pressure than compound Y. |

| | |
|--|--|
| <p>Part D – Point 04</p> <ul style="list-style-type: none"> Choosing the incorrect R value, $8.314 \text{ J/(K} \cdot \text{mol)}$, with the provided pressure in atmospheres Neglecting to convert degrees Celsius to kelvins (using 198 for T) Failing to show work with substitutions Incorrect algebra such as $n = \frac{RT}{PV}$ | <p>Part D – Point 04</p> <ul style="list-style-type: none"> $n = \frac{PV}{RT} = \frac{(2.30 \text{ atm})(12.5 \text{ L})}{\left(0.08206 \frac{\text{L} \cdot \text{atm}}{\text{K} \cdot \text{mol}}\right)(471 \text{ K})} = 0.744 \text{ mol}$ |
|--|--|

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

- Complex Molecular Geometries:** Have students analyze molecular geometries of individual atoms in larger molecules and molecules that have more than one central atom. Some students struggled to analyze the geometry of the Si atom within the relatively complex trimethylsilanol molecule.
- Structural Formula Information:** Point out that in Lewis diagrams, the atomic symbols such as “C” and “Si” represent the nucleus of the atom **and** the core electrons. A fair number of students stated that both *tert*-butyl alcohol and trimethylsilanol had the same number of electrons, ignoring the difference in the number of core electrons between carbon and silicon. The number of *valence* electrons is equivalent, but silicon has an additional occupied electron shell.
- Chemistry Language:** When discussing London dispersion forces and induced dipole moments, coach students to discuss electrons rather than “negative charges” or “charge.”
- Cross-Unit Correlation:** Students are expected to understand several concepts in multiple units related to phases, particularly as related to intermolecular forces (Topic 3.2) and the energetics of phase changes (Topic 6.5).
 - Students should understand that when a substance reaches its boiling point, the substance does not all instantly vaporize, but that the gas and liquid phases are in equilibrium with each other until enough energy has been absorbed to convert all the liquid to the gas phase.
 - Students should also understand that liquids *do* have vapor pressure; a fair number of responses indicated that compound Y had “no vapor pressure” because it was a liquid below its boiling point.
 - Emphasize that the bonds within molecules do not break or form during phase changes. The creation of particle diagrams and other representations may assist with understanding this concept.
- Compare and Contrast:** Coach students to address *all* substances in the prompt when asked to choose or compare substances. In Part C, many responses only addressed compound X without any reference to compound Y.
- Explain/Justify:** Have students practice answering explanation and justification questions on homework assignments, quizzes, and tests, using precise scientific language. In Part C, answers that clearly had a claim followed by both evidence and reasoning were more likely to earn the point. A CER table (Claim – Evidence – Reasoning) can help students organize their responses and ensure they do not omit a key part of their argument.
- Be Explicit:** Coach students to avoid using nonspecific pronouns such as “it,” as “it” does not clearly communicate which compound they mean. Instead, encourage students to use the specific chemical substance (name or formula).

- **Show Work:** Remind students to show all work with substitutions for all calculations, including relevant units, along with the final answer. Simply writing $PV = nRT$ does not constitute “work” for a calculation.
- **Mathematical Practice:** Students need much more practice solving problems by rearranging mathematical equations to solve for the required variable, as algebraic errors are very common. Encourage students to write legibly. Students who make a mistake and cannot fully erase it should cross it out and then rewrite the answer in a box.

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 and assign topic questions for Topics 2.7, 3.1, 3.2, 3.4, and 6.5
- Teachers can share the [Write This, Not That!](#) resource posted by Nora Walsh to the [AP Chemistry Online Community](#). This can be referenced throughout the year to encourage students to build better skills in explaining concepts and providing chemically accurate details in their written responses.
- Teachers can also create custom quizzes from previously administered AP Exam items from the Question Bank and filter for Skills 6.B, 6.C, 6.C, 6.D, and 6.E.
- Teachers can refer to the Preparing for the AP Exam section in Unit 3 of the *AP Chemistry Course and Exam Description* (page 55) for further details about the challenges students face regarding phase changes and intermolecular forces.

Question 6

Task: Zn and Al Galvanic Cell

Topic: Galvanic Cells, Redox reactions, Stoichiometry, Cell Potential

| | Max Points: | Mean Score: |
|--------------------------|-------------|-------------|
| Point 01 | 1.0 | 0.49 |
| Point 02 | 1.0 | 0.52 |
| Point 03 | 1.0 | 0.10 |
| Point 04 | 1.0 | 0.23 |
| Overall Mean Score: 1.34 | | |

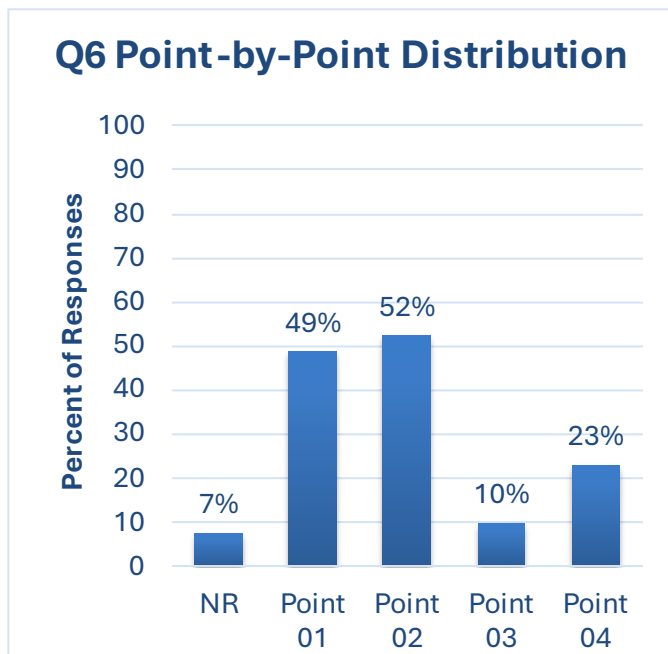
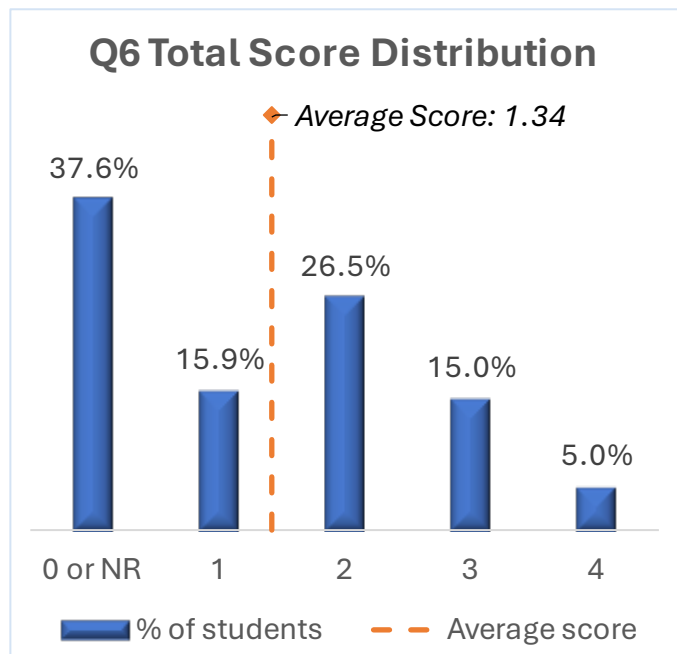
What were the responses to this question expected to demonstrate?

Question 6 presented students with questions about galvanic cells featuring Zn as one of the half-cells.

- Part A requires students to write the half-reaction for the oxidation reaction at the anode. The intent was for students to use the table of standard reduction potentials and the cell description (galvanic, Zn(s) electrode loses mass and Al(s) electrode gains mass) to determine that Al was the anode of the cell, and then to write the half-reaction for the oxidation of Al at the anode. (Learning Objective 9.8.A and Skill 5.E from the *AP Chemistry Course and Exam Description*)
- Part B requires students to write the balanced net ionic equation that occurs as the galvanic cell operates. The intent was for students to correctly add the two half-reactions given in the prompt for the Al and Zn half-cells, taking into account both what is oxidized and reduced as well as ensuring electrons are balanced for the overall reaction. (4.9.A; 5.E)
- Part C requires students to make a quantitative prediction of which electrode's mass would change by a greater amount after the cell operated for a certain time. The intent was for students to relate the stoichiometry of the reaction to the actual operation of the cell in order to compare relative masses of the Al anode and the Zn cathode that would react during the operation of the galvanic cell. (4.5.A; 6.D)
- Part D asks students to identify from a table of standard reduction potentials the half-reaction that, when combined with the Zn half-reaction, would generate the largest standard cell potential. The intent was to assess both how to use a standard reduction table to make predictions of relative voltages and how to calculate the value of that voltage. (9.9.A; 2.B)

How well did the responses address the course content related to this question? How well did the responses integrate the skill(s) required on this question?

The mean score for Question 6 was 1.34 out of a possible 4 points. The total score distribution and the point-by-point distribution on this question are shown in the following figures.



- Part A was a moderately accessible entry point for students. Students who earned the point were able to use information from the prompt about the changes in mass of the Al and Zn electrodes, or the overall E_{cell}° , to correctly select that Al was the anode of the galvanic cell. Respondents then were able to write the correct half reaction (oxidation) that occurred at the anode.
- Part B was the most accessible point in the question. With the proper identification of the anode in Part A, students were able to successfully utilize the given half-reactions to balance the electrons transferred in the reaction from Al to Zn. The sum of the balanced half-reactions then yielded the correct balanced net ionic equation for the galvanic cell.
- Part C was extremely challenging for students and the least accessible point in the question. All successful responses either implicitly or explicitly realized that a constant number of electrons must be transferred from the Al to the Zn and then appropriately calculated the change in mass of each electrode, associated with the electron transfer, from the stoichiometry of the reaction.
- Part D was also very challenging for students. Successful responses recognized that while Zn had to be one of the half-cells, that *did not require Zn to be the cathode of the cell* as it was in parts A–C. Consequently, as the table contained another metal (Au) whose reduction potential was more positive than Zn, combining the most positive reduction potential (Au) with the oxidation of Zn would result in the maximum voltage.

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 – Point 01</p> <ul style="list-style-type: none"> Identifying Al as the anode but writing the reduction of Al as the reaction that occurs at the anode: $\text{Al}^{3+}(\text{aq}) + 3 \text{e}^{-} \rightarrow \text{Al}(\text{s})$ Neglecting to show electrons as a product of the oxidation half-reaction: <ul style="list-style-type: none"> $\text{Al}(\text{s}) \rightarrow \text{Al}^{3+}(\text{aq})$ $\text{Al}(\text{s}) - 3 \text{e}^{-} \rightarrow \text{Al}^{3+}(\text{aq})$ Identifying Zn as the anode | <p>Part A – Point 01</p> <ul style="list-style-type: none"> $\text{Al}(\text{s}) \rightarrow \text{Al}^{3+}(\text{aq}) + 3 \text{e}^{-}$ |
| <p>Part B – Point 02</p> <ul style="list-style-type: none"> Neglecting to balance the net ionic equation for both species and charge Utilizing fractional stoichiometric coefficients in the net ionic equation Writing the molecular equation for the overall reaction: $3 \text{Zn}(\text{NO}_3)_2(\text{aq}) + 2 \text{Al}(\text{s}) \rightarrow 2 \text{Al}(\text{NO}_3)_3(\text{aq}) + 3 \text{Zn}(\text{s})$ Neglecting to cancel electrons or spectator ions from the complete ionic equation | <p>Part B – Point 02</p> <ul style="list-style-type: none"> $2 \text{Al}(\text{s}) + 3 \text{Zn}^{2+}(\text{aq}) \rightarrow 2 \text{Al}^{3+}(\text{aq}) + 3 \text{Zn}(\text{s})$ |
| <p>Part C – Point 03</p> <ul style="list-style-type: none"> Neglecting to use both the stoichiometry of the reaction AND the molar masses to make a comparison. Many responses stated that Zn would change by a greater amount simply because 3 moles of Zn would be generated per 2 moles of Al. Although true, as the question asks for a mass comparison, it is essential to note that the molar mass of Zn is greater. Simply making a mole comparison based on the stoichiometry is insufficient. Inverting the stoichiometric ratio between Al and Zn as part of the calculation, i.e., $\left(\frac{2 \text{ mol Al}}{3 \text{ mol Zn}}\right)$, leading to incorrect values (and units) of the mass changes. | <p>Part C – Point 03</p> <ul style="list-style-type: none"> When 50.0 g of Al reacts, 182 g of Zn would be formed as shown by the calculations below: $50.0 \text{ g Al} \times \frac{1 \text{ mol Al}}{26.98 \text{ g Al}} \times \frac{3 \text{ mol Zn}}{2 \text{ mol Al}} \times \frac{65.38 \text{ g Zn}}{1 \text{ mol Zn}} = 182 \text{ g Zn}$ Thus, the change in mass of the Zn is greater. For every 2 moles of Al that react, 3 moles of Zn would be produced. 2 moles of Al have a mass of 53.96 g : $2 \text{ mol Al} \left(\frac{26.98 \text{ g Al}}{1 \text{ mol Al}} \right) = 53.96 \text{ g Al}$ Three moles of Zn have a mass of 196 g : $3 \text{ mol Zn} \left(\frac{65.38 \text{ g Zn}}{1 \text{ mol Zn}} \right) = 196.1 \text{ g Zn}$ |

| | |
|--|---|
| <ul style="list-style-type: none"> Considering the problem to be one of a limiting reactant between the Zn electrode and the Al electrode. This is conceptually incorrect as Zn is a product of the reaction. Simply comparing the number of moles in 50.0 g of Al (1.85 mol) and 50.0 g of Zn (0.765 mol) and stating the change in Zn was larger (because $50.0 - 0.765$ is greater than $50.0 - 1.85$). Implying that the Al electrode would have the greater change in mass because it lost more electrons than Zn gained, reasoning the loss or gain in mass was coming from the change in the number of electrons alone. | <p>Therefore, the change in mass of the Zn electrode is greater.</p> |
| <p>Part D – Point 04</p> <ul style="list-style-type: none"> Neglecting to recognize that Zn can act as the anode in the cell that would generate the maximum voltage. Many responses assumed that Zn must remain the cathode and would calculate the voltage generated from a cell with Be as the anode and Zn as the cathode. This cell would have a voltage of 1.09 V: $E_{cell}^{\circ} = 1.85 \text{ V} - 0.76 \text{ V} = 1.09 \text{ V}.$ Disregarding the prompt and calculating the maximum voltage that could be generated from the metals in the table with Be as the anode and Au as the cathode with a voltage of 3.35 V: $E_{cell}^{\circ} = 1.50 \text{ V} + 1.85 \text{ V} = 3.35 \text{ V}.$ Forgetting that E° values are intensive properties that do not depend on the stoichiometric coefficients of the reaction. Hence, the following calculation with a Zn anode and a Au cathode would be incorrect: $E_{cell}^{\circ} = 2(1.50 \text{ V}) + 3(0.76 \text{ V}) = 5.28 \text{ V}.$ Utilizing an incorrect algorithmic/algebraic approach to calculate E_{cell}°. For example, <ul style="list-style-type: none"> $E_{cell}^{\circ} = -0.76 \text{ V} - 1.50 \text{ V} = -2.26 \text{ V}$ $E_{cell}^{\circ} = -0.76 \text{ V} + 1.50 \text{ V} = 0.74 \text{ V}$ Simply writing a voltage with no calculation or justification. | <p>Part D – Point 04</p> <ul style="list-style-type: none"> Using Au as the cathode and Zn as the anode, the following half-reactions occur in the cell: <ul style="list-style-type: none"> $\text{Zn} \rightarrow \text{Zn}^{2+} + 2 e^{-} \quad E^{\circ} = 0.76 \text{ V}$ $\text{Au}^{3+} + 3 e^{-} \rightarrow \text{Au} \quad E^{\circ} = 1.50 \text{ V}$ $E_{cell}^{\circ} = 0.76 \text{ V} + 1.50 \text{ V} = 2.26 \text{ V}$ $1.50 \text{ V} - (-0.76 \text{ V}) = 1.50 \text{ V} + 0.76 \text{ V} = 2.26 \text{ V}$ |

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

Electrochemistry is often a topic that is compressed in the teaching of AP Chemistry because of its position in most textbooks. However, exploring the electrochemical cell is a terrific capstone topic that can combine a review of redox reactions and stoichiometry while applying calculations of thermodynamic favorability. Students need opportunities to explore working with galvanic cells, and they need practice describing the operation of the cell in terms of the underlying chemical reactions that occur at each electrode. Specific things to focus on include:

- **Galvanic Cell Construction:** Build one or more galvanic cells that actually perform mechanical or electrical work. For example, strips of magnesium and copper can be placed in vinegar or orange juice to power a quartz clock mechanism that runs on a single AA battery (these mechanisms can be found at any craft store). Discuss the flow of electrons from magnesium to the copper through the mechanism and have students observe that the magnesium anode physically degrades as the reaction proceeds. This allows students to understand that any electrochemical cell made is simply a specific application of the underlying redox reaction.
- **Cell Diagrams:** Have students diagram the components of a galvanic cell and practice writing both the overall reaction of the cell and the half-reactions that take place at each electrode.
- **Net Ionic Equations:** Provide practice writing net ionic equations throughout the year as students encounter the main types of reactions that occur in the course (precipitation, acid-base, and redox).
- **Stoichiometry:** Continue to emphasize stoichiometric calculations as students proceed through studies of thermodynamics, kinetics, and equilibrium.
- **Using Standard Reduction Potentials:** Have students utilize a standard reduction table to both generate thermodynamically favorable reactions for redox reactions and then use the table to calculate the E° value of the cell, emphasizing the intensive nature of E° in the calculations. A terrific associated lab activity is to have students build several electrochemical cells (or have different groups build different cells) and compare the voltage obtained in lab with theoretical calculations.
- **Faraday's Law:** Explore Faraday's law quantitatively both in problem solving and experimentation (electrolysis experiments in which a solid is plated on an electrode are particularly instructive).

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 and assign topic questions for Topics 4.5, 4.9, 9.8, and 9.9.
- Teachers can use AP Classroom to direct students to the AP Exam On-Demand Review 2023 Session 7: FRQ (Long) C₂H₅OH Galvanic Cell.
- Teachers can utilize the [Electrolysis](#) simulation from Pearson and the [Galvanic/Voltaic Cells](#) simulation from AACT to allow students to explore what happens at the atomic level as electrolytic and Galvanic cells operate. Students can explore concentration effects on cell potential using [Galvanic/Voltaic Cells 2](#).
- To help students practice justifying their claims using evidence and reasoning, teachers can create custom quizzes from previously administered AP Exam items from the Question Bank and filter for Skills 6.B, 6.C, 6.D, and 6.E.

Question 7

Task: Glycolate

Topic: Molecular Structure of Acids and Bases, Calculating the Equilibrium Constant, Weak Acid and Base Equilibria, Catalysis

| | Max Points: | Mean Score: |
|---------------------|-------------|-------------|
| Point 01 | 1.0 | 0.61 |
| Point 02 | 1.0 | 0.41 |
| Point 03 | 1.0 | 0.48 |
| Point 04 | 1.0 | 0.51 |
| Overall Mean Score: | 2.00 | |

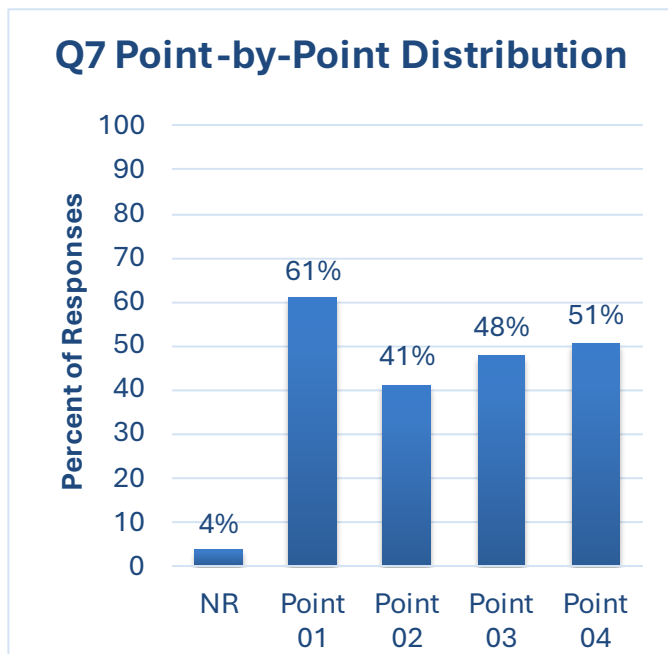
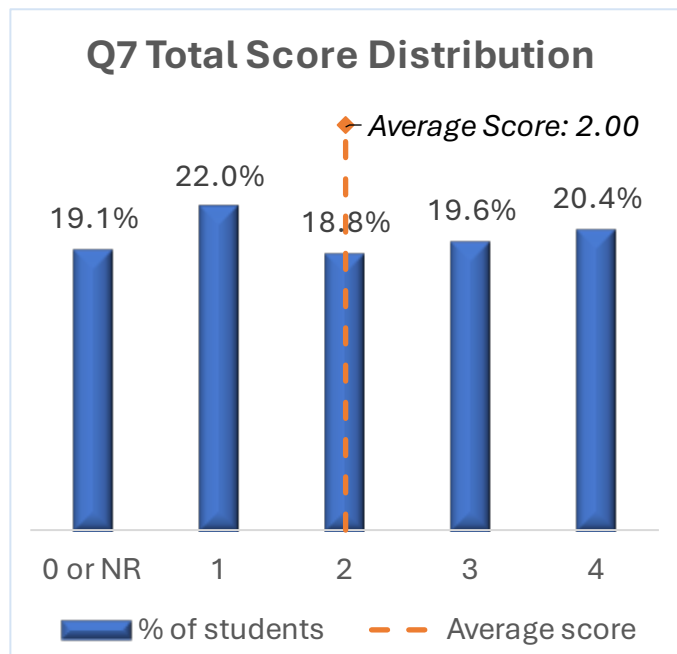
What were the responses to this question expected to demonstrate?

Question 7 presents items relating to the glycolate ion's properties as a base.

- Part A requires students to identify the atom that would be protonated to produce glycolic acid. The intent was for responses to recognize that an oxygen atom in the carboxylate group would be protonated. (Learning Objective 8.6.A and Skill 3.B from the *AP Chemistry Course and Exam Description*)
- Part B (i) requires students to calculate the equilibrium constant, K_b , of the glycolate ion, given the concentrations of glycolate and hydroxide for a solution. The intent was for students to recognize that the equilibrium concentration of glycolic acid is the same as the hydroxide ion concentration. Because the glycolate ion concentration is also known, the intent was for the student to substitute these values into the K_b expression provided to calculate the value of K_b . (7.4.A; 5.F)
- Part B (ii) requires students to calculate the equilibrium constant, K_a for glycolic acid using the equilibrium constant, K_b , of the glycolate ion calculated in B (i) and the autoionization constant of water, K_w , and $K_w = K_a \times K_b$, provided in the Equations and Constants materials. The intent was for students to mathematically rearrange $K_w = K_a \times K_b$ and substitute in the correct values to calculate K_a . (8.3.A; 5.F)
- Part C requires students to verify a claim that the hydronium ion is a catalyst in the proposed hydrolysis mechanism provided for methyl glycolate and to justify their answer citing the evidence from the proposed mechanism. The intent was for students to claim that the hydronium ion is a catalyst and to state a justification based on the ion being a consumed reactant in the first step and subsequently being regenerated as a product in the second step of the proposed mechanism while not appearing in the overall equation. (5.11.A; 6.C)

How well did the responses address the course content related to this question? How well did the responses integrate the skill(s) required on this question?

The mean score for Question 7 was 2.00 out of a possible 4 points. The total score distribution and the point-by-point distribution on this question are shown in the following figures.



- Part A was very accessible for students. Correct responses circled an oxygen atom in the carboxylate group of the glycolate ion.
- Part B (i) was somewhat accessible to students. Correct responses were able to determine the concentrations at equilibrium of all the components, typically using an ICE table, and using them to calculate an equilibrium constant. The response required knowledge of the reaction of a base with water, the relationship between initial and equilibrium concentrations (or the use of an ICE table), and the calculation of an equilibrium constant. The equilibrium constant expression was provided.
- Part B (ii) was slightly more accessible to students. Correct responses determined the equilibrium constant, K_a , for glycolic acid using the equilibrium constant, K_b , of the glycolate ion from B (i), and the autoionization constant of water, K_w , which is provided on the equations sheet. The response required recognition of the proper equation, $K_w = K_a \times K_b$, and knowledge of correct mathematical manipulation to calculate K_a .
- Part C was moderately accessible to students. Correct responses were able to identify that a catalyst was consumed as a reactant in a reaction mechanism and then regenerated as a product in a subsequent step of the mechanism, demonstrating the properties of a catalyst in a reaction mechanism. The response required knowledge of how a catalyst is represented in a mechanism and not just the properties of a catalyst (increase in the reaction rate) or the reason a catalyst works (the lowering of the activation energy by providing an alternative pathway).

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 – Point 01</p> <ul style="list-style-type: none"> Misinterpreting the prompt by circling the alcohol hydrogen in the glycolate ion; that would be more likely to donate a hydrogen when reacting with water. Choosing the oxygen atom on the alcohol group of the glycolate ion. | <p>Part A – Point 01</p> <ul style="list-style-type: none"> Circling either of the oxygen atoms of the carboxylate group that are equivalent via resonance structures |
| <p>Part B (i) – Point 02</p> <ul style="list-style-type: none"> Using the concentration of the hydroxide ion as the value of K_b and solving for the hydroxide ion concentration. $1.3 \times 10^{-5} = \frac{x^2}{2.5}$ Using the hydroxide ion concentration for both the glycolic acid and the glycolate ion concentration. This results in $K_b = 1.3 \times 10^{-5}$. Using the glycolate concentration for the glycolic acid concentration, then using 1 for the glycolate concentration. This results in $K_b = 3.3 \times 10^{-5}$. Not recognizing the hydroxide ion and glycolic acid concentrations are the same and using 1 for the glycolic acid concentration. This results in $K_b = 5.2 \times 10^{-6}$. | <p>Part B (i) – Point 02</p> <ul style="list-style-type: none"> Using the provided concentration equilibrium for hydroxide ion and realizing this is also the equilibrium concentration for glycolic acid in the numerator of the expression. Correct responses either subtracted the $[\text{OH}^-]_{eq}$ from the initial $[\text{C}_2\text{H}_3\text{O}_3^-]$ ion or realized that $[\text{OH}^-]_{eq}$ is not significant compared to the initial $[\text{C}_2\text{H}_3\text{O}_3^-]$. The resulting $K_b = 6.8 \times 10^{-11}$. $K_b = \frac{[\text{HC}_2\text{H}_3\text{O}_3][\text{OH}^-]}{[\text{C}_2\text{H}_3\text{O}_3^-]}$ $K_b = \frac{(1.3 \times 10^{-5})(1.3 \times 10^{-5})}{(2.5 - 1.3 \times 10^{-5})} = 6.8 \times 10^{-11}$ |
| <p>Part B (ii) – Point 03</p> <ul style="list-style-type: none"> Calculating K_a as the reciprocal of K_b: $K_a = 1 / K_b$ Calculating K_a by subtracting K_b from K_w: $K_a = K_w - K_b$ or $K_a = 14 - K_b$ | <p>Part B (ii) – Point 03</p> <ul style="list-style-type: none"> Using the proper equation from the equation table, substituting the correct values of K_w and K_b, and correctly calculating the answer $K_a = \frac{K_w}{K_b} = \frac{1.0 \times 10^{-14}}{6.8 \times 10^{-11}} = 1.5 \times 10^{-4}$ |

| | |
|---|---|
| <p>Part C – Point 04</p> <ul style="list-style-type: none"> The hydronium ion cannot be a catalyst because it is a spectator ion. A catalyst increases the rate or speeds up a reaction (definition is unrelated to the mechanism). A catalyst provides a pathway with lower activation energy (definition is unrelated to the mechanism). Identifies the hydronium ion as an intermediate and not a catalyst. Vague statements that apply to either a catalyst or an intermediate, such as the hydronium ion acts as both a product and a reactant. The response disagrees with the assertion, then correctly states that hydronium ion is a reactant in the first step, then is a product in the second step and therefore cannot be a catalyst. The response did not demonstrate knowledge of the difference between a catalyst and an intermediate. | <p>Part C – Point 04</p> <ul style="list-style-type: none"> Agree, the hydronium ion is a reactant in the first step and is a product in the second step. Additional statements were often added. The following are all true statements: <ul style="list-style-type: none"> The catalyst is not in the overall reaction. The catalyst speeds up the reaction. The catalyst lowers the activation energy. <p>To earn the point, these statements must be accompanied by the first statement, as it answers the question in the prompt.</p> |
|---|---|

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

- Organic Acid/Base Structures:** Instruct students about the structure of organic acids and bases in addition to binary and oxo/inorganic acids.
- Equilibrium Concentrations:** In addition to problems using equilibrium constants to determine equilibrium concentrations, have students complete problems using equilibrium concentrations to determine equilibrium constants.
 - Equilibrium constants characterize chemical properties and chemical reactions, analogous to density, specific heat capacity, and other physical properties characterizing substances.
 - Distinguish pH, pOH, pK_a , and pK_b from $[OH^-]$, $[H^+]$, K_a , and K_b respectively. Encourage students to always show work, label work, and label answers.
- Reaction Mechanisms:** The overall chemical equation is provided as the sum of the individual steps and is there only to validate the proposed mechanism. Questions regarding catalysts, intermediates, and rate-determining steps require evaluation of the individual steps of the mechanism and not the overall reaction equation.
 - Emphasize that the overall reaction equation is only there to show that the proposed mechanism is valid. The overall equation was a distractor; it was common to have responses state that the hydronium ion is a spectator ion or include it as a step in the reaction mechanism. Increase correct usage of vocabulary regarding intermediates, catalysts, reactants, and products.
 - Give students practice evaluating written explanations, such as through peer review of their classmates' justifications and/or explanations.

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 and assign topic questions for Topics 5.11, 7.3, 7.4, 8.3, and 8.6.
- Teachers can create custom quizzes from previously administered AP Exam items from the Question Bank and filter for Topics 7.4, 7.5, 7.6, 7.11, and 8.3 that are coupled with Skill 5.F.
- Teachers can have students analyze and critique [sample responses from AP Central](#) and rewrite them for clarity and chemical accuracy.